Self-Adjusting Networks: Vision, Solutions, Challenges

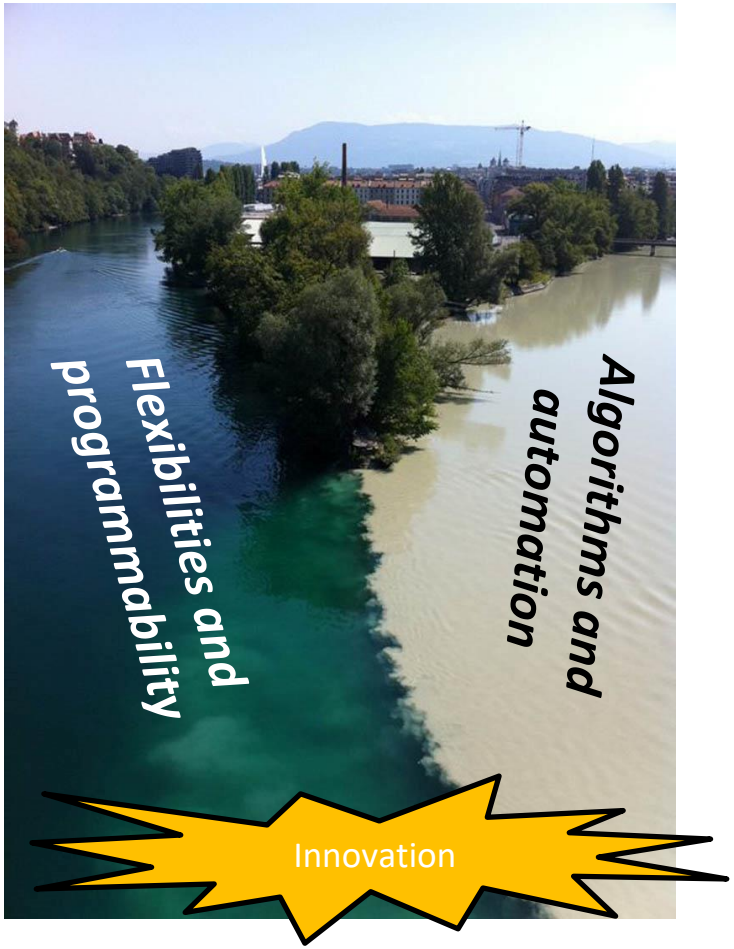
Stefan Schmid

"We cannot direct the wind,
but we can adjust the sails."

(Folklore)

Acknowledgements:

It`s a Great Time to Be a Networking Researcher!



Credits: George Varghese

It`s a Great Time to Be a Networking Researcher!

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Enables and motivates **self-adjusting networks**!

It’s High Time!

Explosive Traffic

Datacenters (“hyper-scale”)

+network

Interconnecting networks:
a **critical infrastructure**
of our digital society.

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Credits: Marco Chiesa

It’s High Time!

Reality vs Requirements

Today, dependability requirements stand in contrast with reality:

Countries disconnected

Data Centre ▸ Networks

Google routing blunder sent Japan's Internet dark on Friday

Another big BGP blunder

By Richard Chirgwin 27 Aug 2017 at 22:35 40 SHARE ▼

Last Friday, someone in Google fat-thumbed a border gateway protocol (BGP) advertisement and sent Japanese Internet traffic into a black hole.

The trouble began when The Chocolate Factory “leaked” a big route table to Verizon, the result of which was traffic from Japanese giants like NTT and KDDI was sent to Google on the expectation it would be treated as transit.

Passengers stranded

British Airways' latest Total Inability To Support Upwardness of Planes* caused by Amadeus system outage

Stuck on the ground awaiting a load sheet? Here's why

By Gareth Corfield 19 Jul 2018 at 11:16 109 SHARE ▼

Even 911 affected

Officials: Human error to blame in Minn. 911 outage

According to a press release, CenturyLink told department of public safety that human error by an employee of a third party vendor was to blame for the outage

Aug 16, 2018

Duluth News Tribune

SAINT PAUL, Minn. — The Minnesota Department of Public Safety Emergency Communication Networks division was told by its 911 provider that an Aug. 1 outage was caused by human error.

Even tech-savvy companies struggle:

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Even tech-savvy companies struggle:

Mainly: human errors!

Credits: Laurent Vanbever, Nate Foster

Agenda

Three Use Cases

Passau, Germany

Agenda

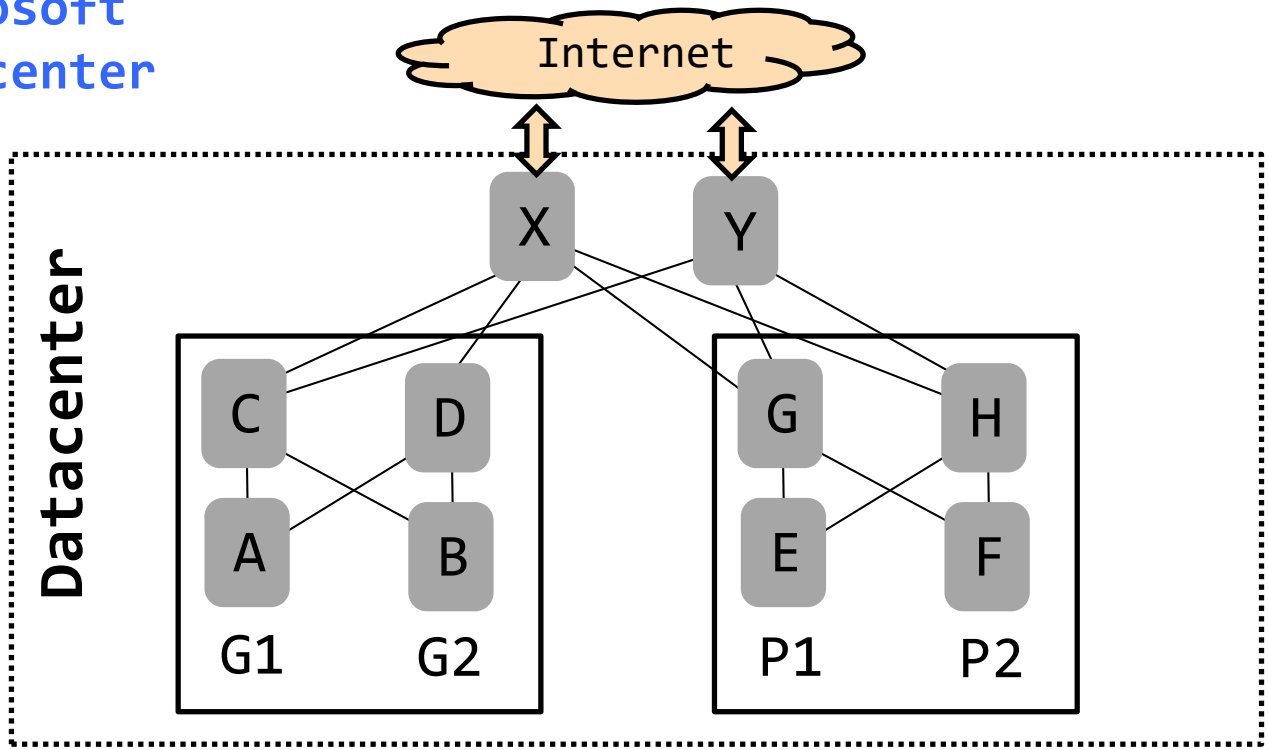
Three Use Cases

Formal methods as a tool!

Motivation: Complexity

Especially Under Failures (Policy Compliance)

Example: BGP in **Microsoft datacenter**



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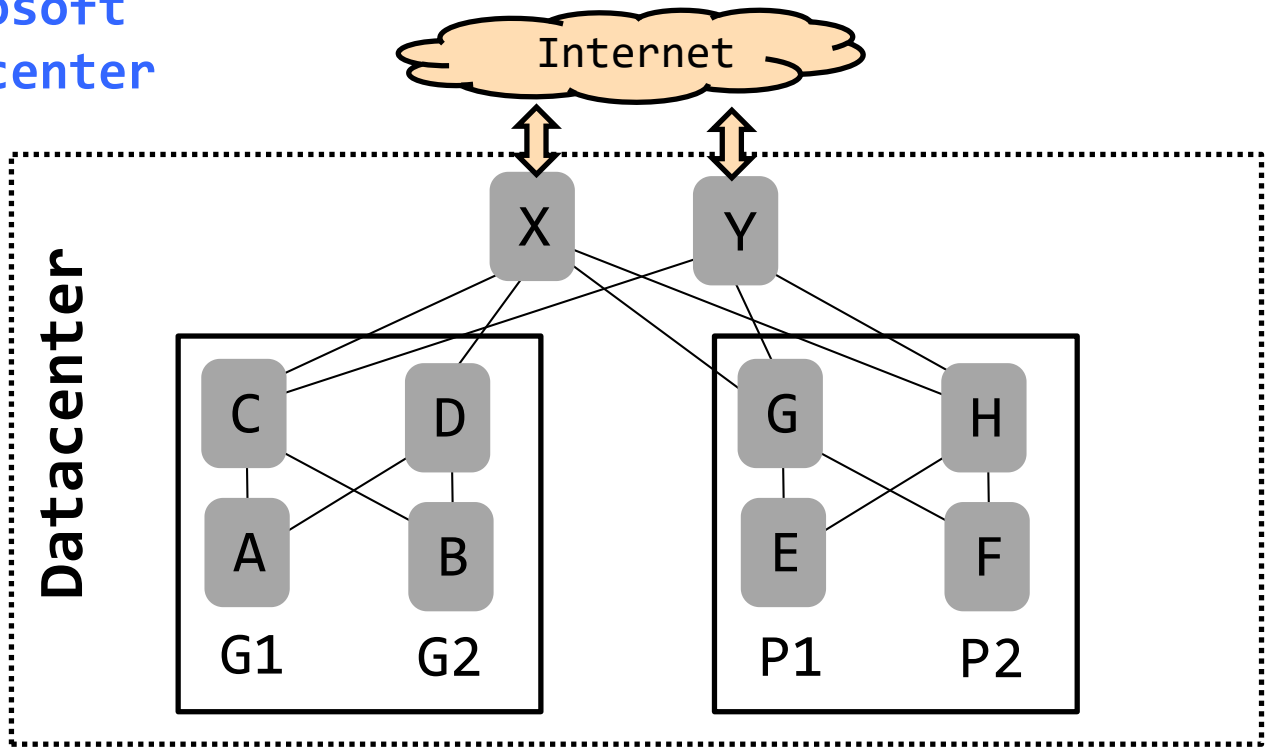

Cluster with globally reachable services

Cluster with internally accessible services

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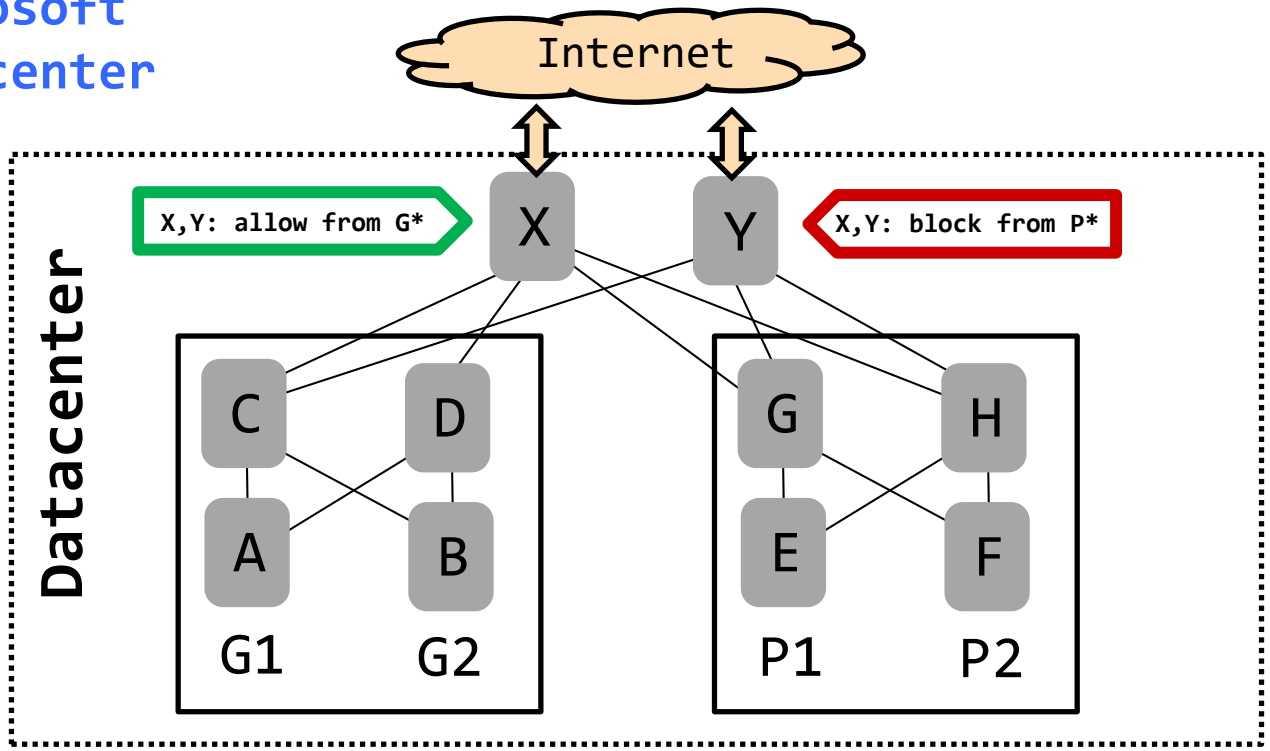

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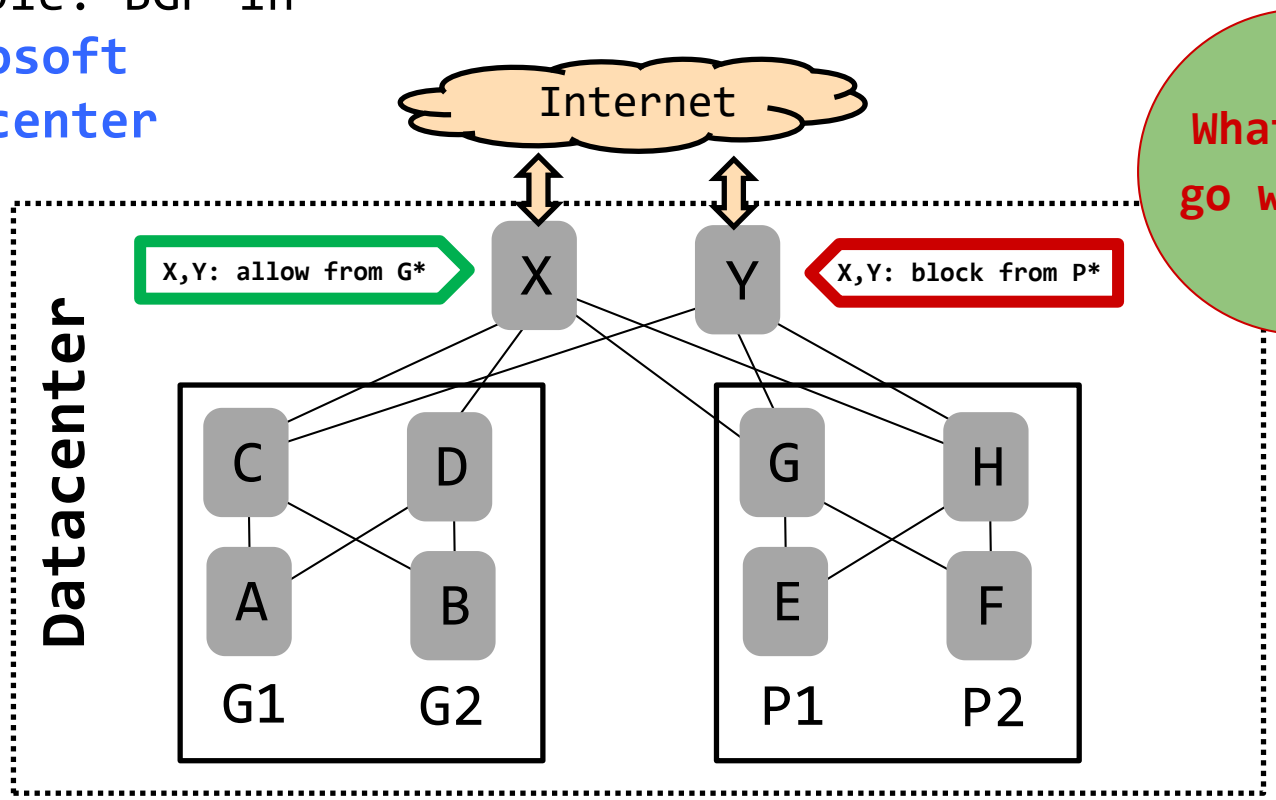

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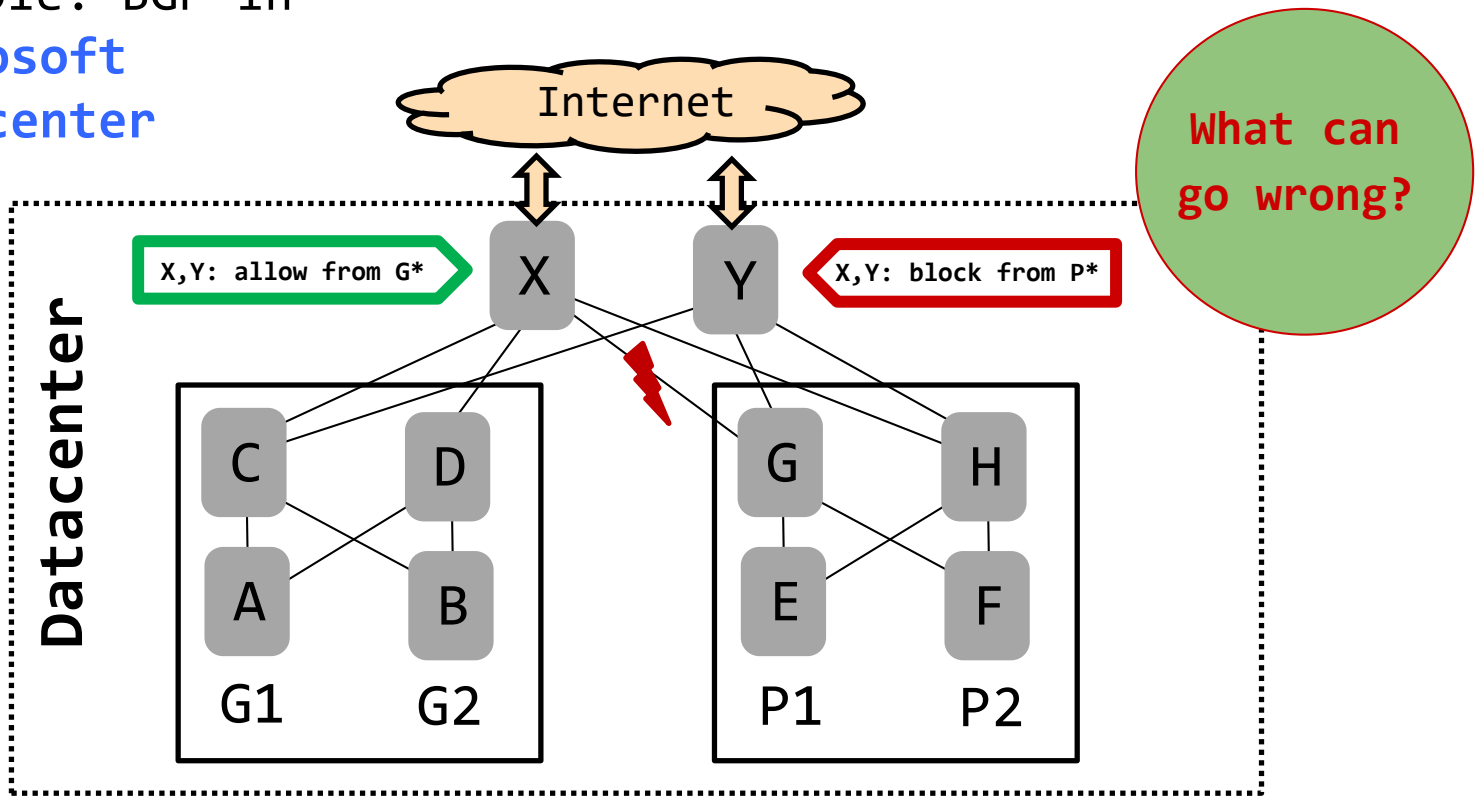

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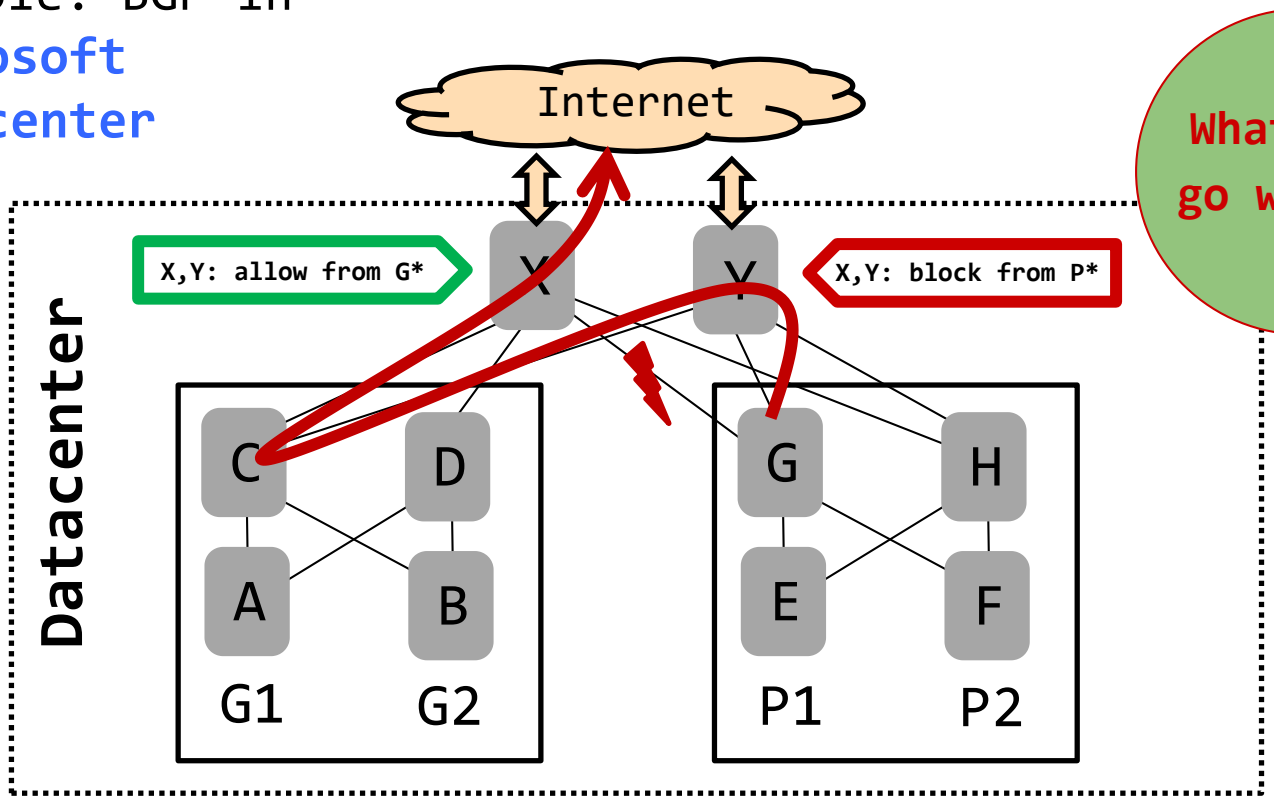
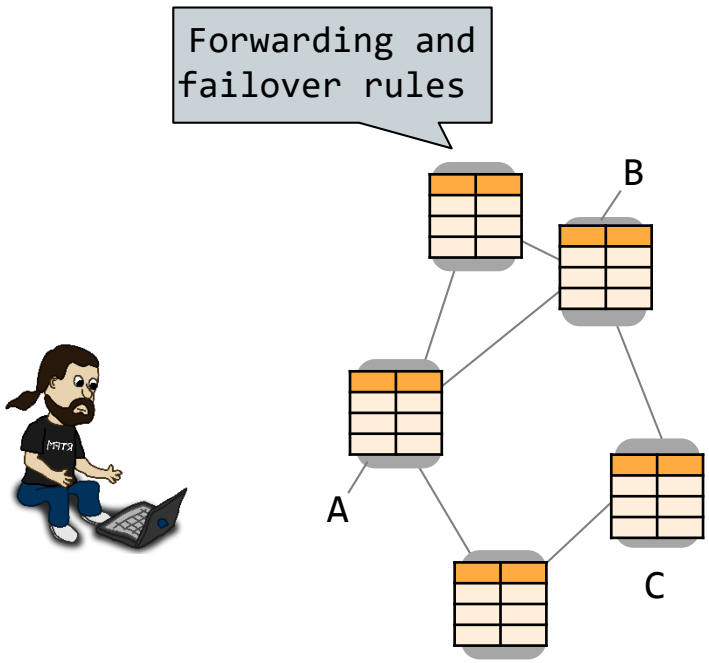


If link (G,X) fails and traffic from G is rerouted via Y and C to X: X announces (does not block) G and H as it comes from C. (Note: BGP.)

Admin’s Responsibilities



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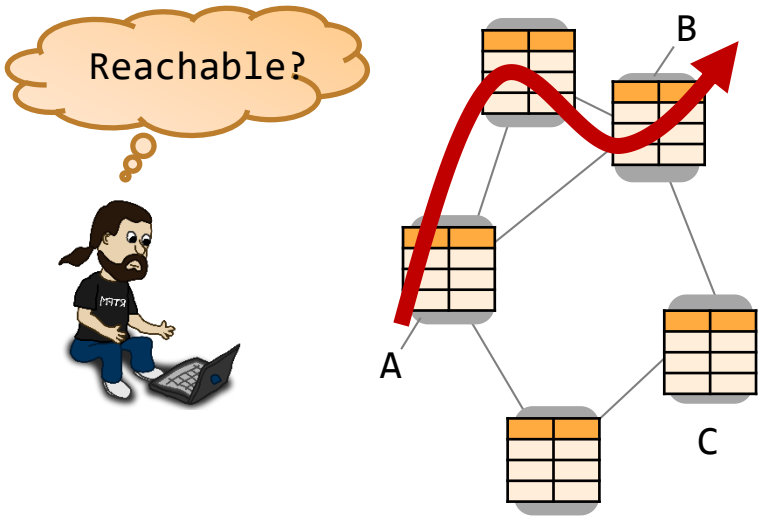
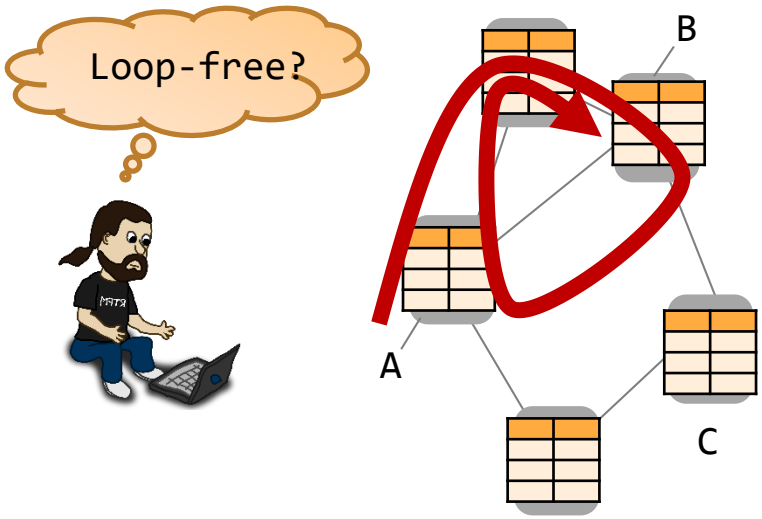


⇢ Reachability: Can traffic from ingress port A reach B?

Admin's Responsibilities



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⇢ Loop-freedom: Do forwarding rules imply loop-free routes?

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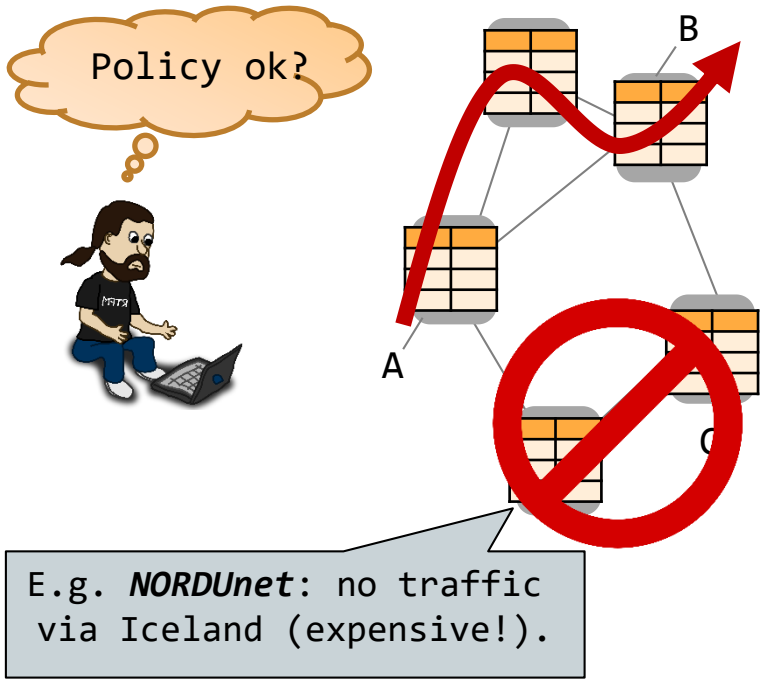

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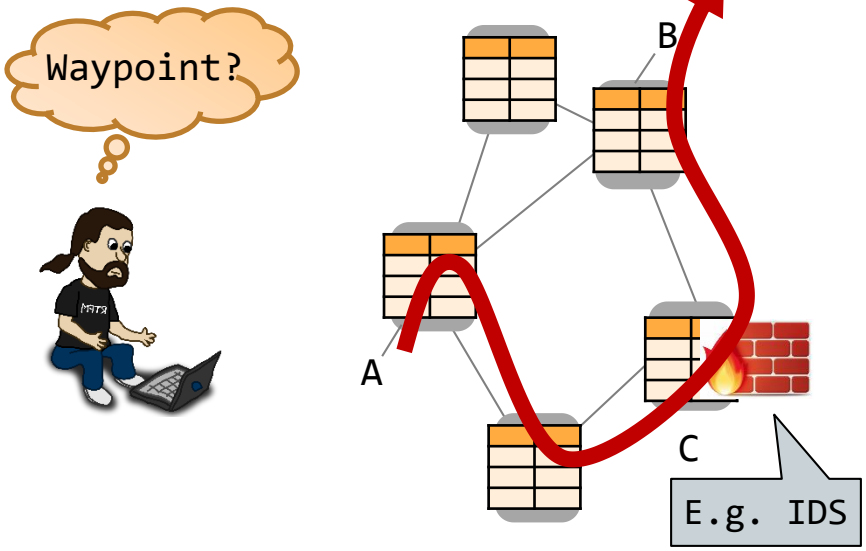

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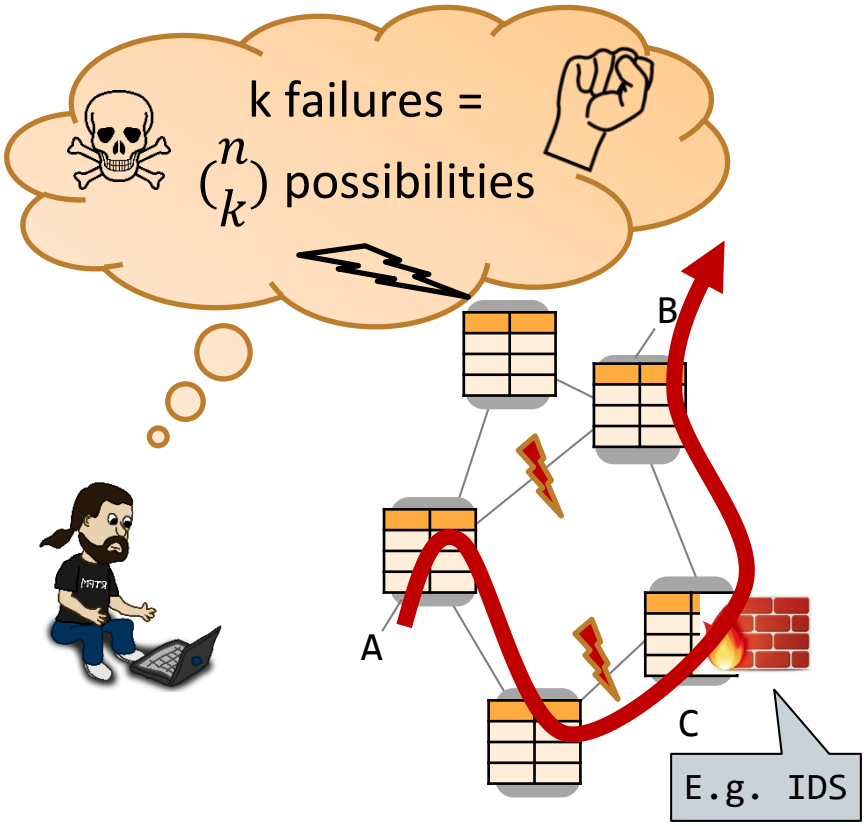

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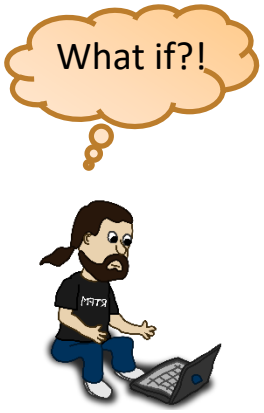
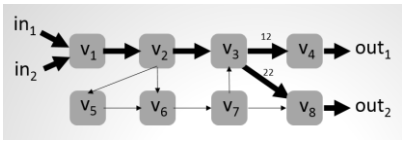
… and everything even under failures?!

A Modern Approach:

Automated Whatif Analysis



FT	In-I	In-Label	Out-I	op
τ_{v_1}	in_1	$\perp$	(v_1, v_2)	$push(10)$
	in_2	$\perp$	(v_1, v_2)	$push(20)$
τ_{v_2}	(v_1, v_2)	10	(v_2, v_3)	$swap(11)$
	(v_1, v_2)	20	(v_2, v_3)	$swap(21)$
τ_{v_3}	(v_2, v_3)	11	(v_3, v_4)	$swap(12)$
	(v_2, v_3)	21	(v_3, v_8)	$swap(22)$
	(v_7, v_3)	11	(v_3, v_4)	$swap(12)$
	(v_7, v_3)	21	(v_3, v_8)	$swap(22)$
τ_{v_4}	(v_3, v_4)	12	out_1	pop
τ_{v_5}	(v_2, v_5)	40	(v_5, v_6)	pop
τ_{v_6}	(v_2, v_6)	30	(v_6, v_7)	$swap(31)$
	(v_5, v_6)	30	(v_6, v_7)	$swap(31)$
	(v_5, v_6)	61	(v_6, v_7)	$swap(62)$
	(v_5, v_6)	71	(v_6, v_7)	$swap(72)$
τ_{v_7}	(v_6, v_7)	31	(v_7, v_3)	pop
	(v_6, v_7)	62	(v_7, v_3)	$swap(11)$
	(v_6, v_7)	72	(v_7, v_8)	$swap(22)$
τ_{v_8}	(v_3, v_8)	22	out_2	pop
	(v_7, v_8)	22	out_2	pop



local FFT	Out-I	In-Label	Out-I	op
τ_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$push(30)$
	(v_2, v_3)	21	(v_2, v_6)	$push(30)$
	(v_2, v_6)	30	(v_2, v_5)	$push(40)$
global FFT	**Out-I**	**In-Label**	**Out-I**	**op**
τ'_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$swap(61)$
	(v_2, v_3)	21	(v_2, v_6)	$swap(71)$
	(v_2, v_6)	61	(v_2, v_5)	$push(40)$
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Router **configurations**
(Cisco, Juniper, etc.)

Compilation

Interpretation

$$pX \Rightarrow qXX$$
$$pX \Rightarrow qYX$$
$$qY \Rightarrow rYY$$
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$$rX \Rightarrow pX$$

Formal language
which supports
automated analysis

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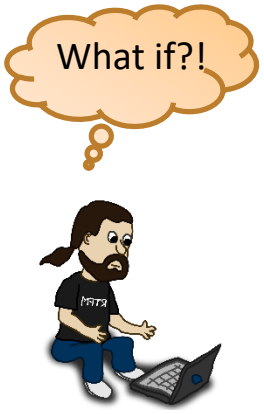

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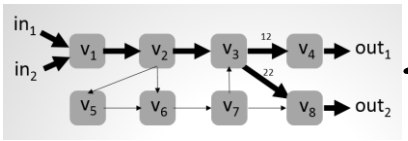

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On request or regularly.

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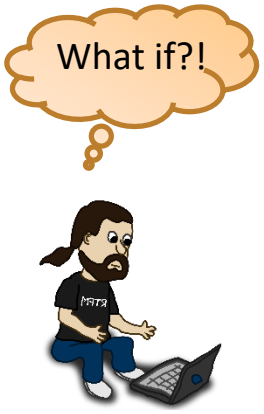

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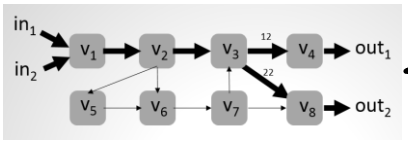

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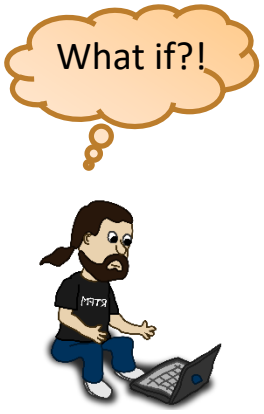

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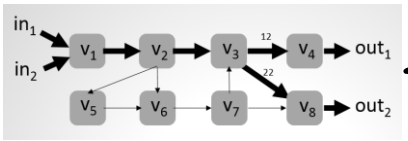
	(v_7, v_8)	22	out_2	pop



local FFT	Out-I	In-Label	Out-I	op
τ_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$push(30)$
	(v_2, v_3)	21	(v_2, v_6)	$push(30)$
	(v_2, v_6)	30	(v_2, v_5)	$push(40)$
global FFT	**Out-I**	**In-Label**	**Out-I**	**op**
τ'_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$swap(61)$
	(v_2, v_3)	21	(v_2, v_6)	$swap(71)$
	(v_2, v_6)	61	(v_2, v_5)	$push(40)$
	(v_2, v_6)	71	(v_2, v_5)	

Compilation

On request or regularly.

Fix/**synthesize**

$pX \Rightarrow qXX$
$pX \Rightarrow qYX$
$qY \Rightarrow rYY$
$rY \Rightarrow r$
$rX \Rightarrow pX$

Router **configura**
(Cisco, Juniper,

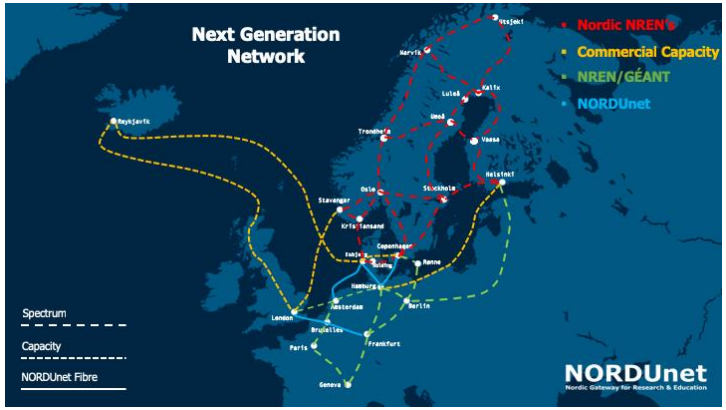
l language
supports
ed analysis

Challenge:

Hard Even for Computers?

⇢ NORDUnet: provider for Nordic countries

⇢ 24 MPLS routers, running Juniper OS, >30,000 labels!



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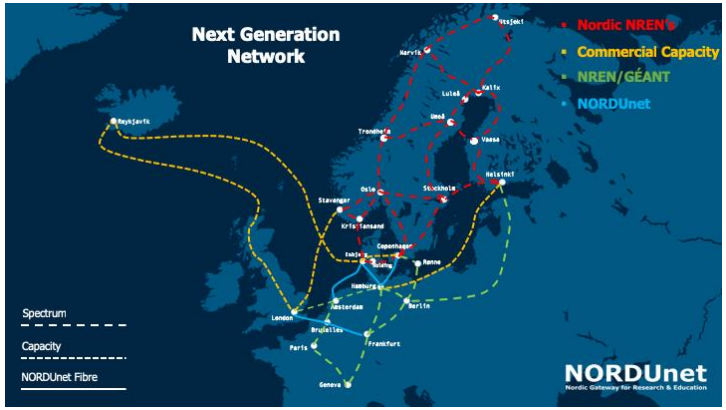

For specific networks such as MPLS: feasible and fast!
Tools such as P-Rex or AalWiNes do it in secs for MPLS: reduction to automata theory, polynomial-time.

Formal methods!

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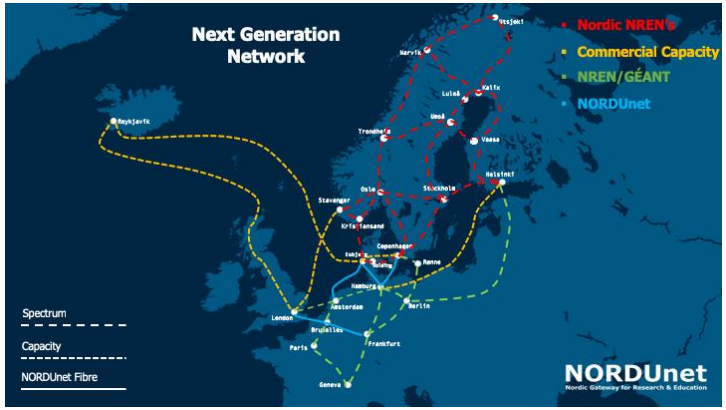

For specific networks such as MPLS: feasible and fast!
Tools such as P-Rex or AalWiNes do it in secs for MPLS: reduction to automata theory, polynomial-time.
But general networks more challenging.

Formal methods!

Fixing&Synthesis: Harder

⇢ Approaches: ***Petri games***, Stackelberg games, UPPAAL Stratego…

⇢ But ***synthesis slower*** than verification

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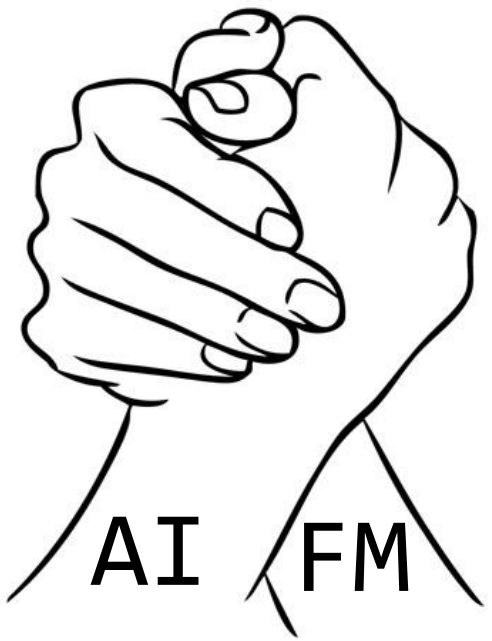
⇢ ***Ideally AI+FM***: guarantees from formal methods, performance from AI

⇢ For example: synthesize with AI then verify with formal methods

⇢ Examples: DeepMPLS, DeepBGP, …



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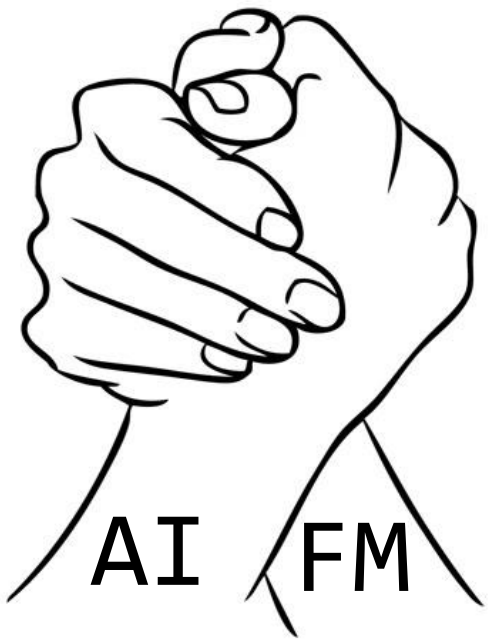

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⇢ Examples: DeepMPLS, DeepBGP, …

… and what about quantitative properties?

A Possible Starting Point:

The AalWiNes Tool

Online demo: https://demo.aalwines.cs.aau.dk/
Source code: https://github.com/DEIS-Tools/AalWiNes
Paper: https://schmiste.github.io/conext20.pdf

Agenda

Three Use Cases

Passau, Germany

Agenda

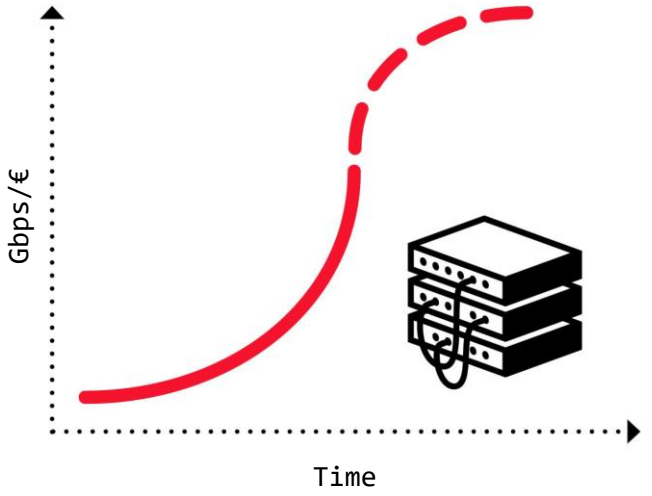
Three Use Cases

On lower layers!

Let’s go back to datacenter use case:

Moore’s Law of Datacenters

- ⇢ Recall: **explosive growth** of demand
- ⇢ Problem: network equipment reaching capacity limits
  - ⇀ Transistor density rates stalling
  - ⇀ “End of **Moore‘s Law** in networking”
- ⇢ Hence: more equipment, larger networks
- ⇢ Resource intensive and: **inefficient**



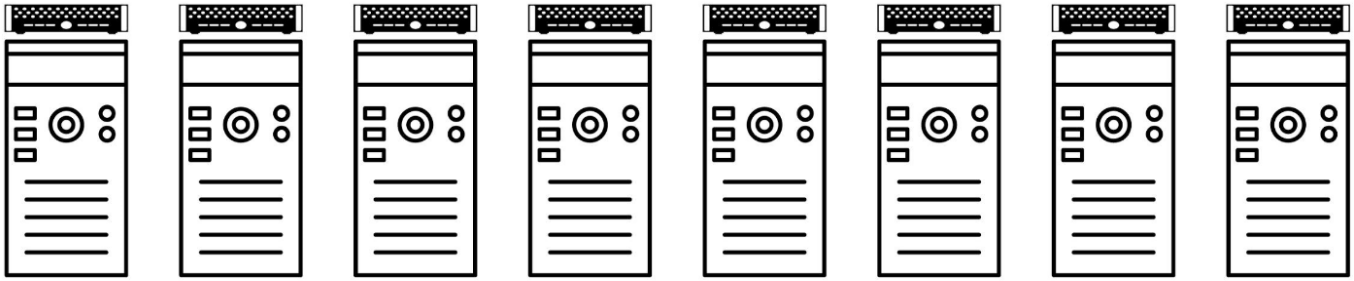
[1] Source: Microsoft, 2019

Annoying for companies,
opportunity for researchers

Root Cause

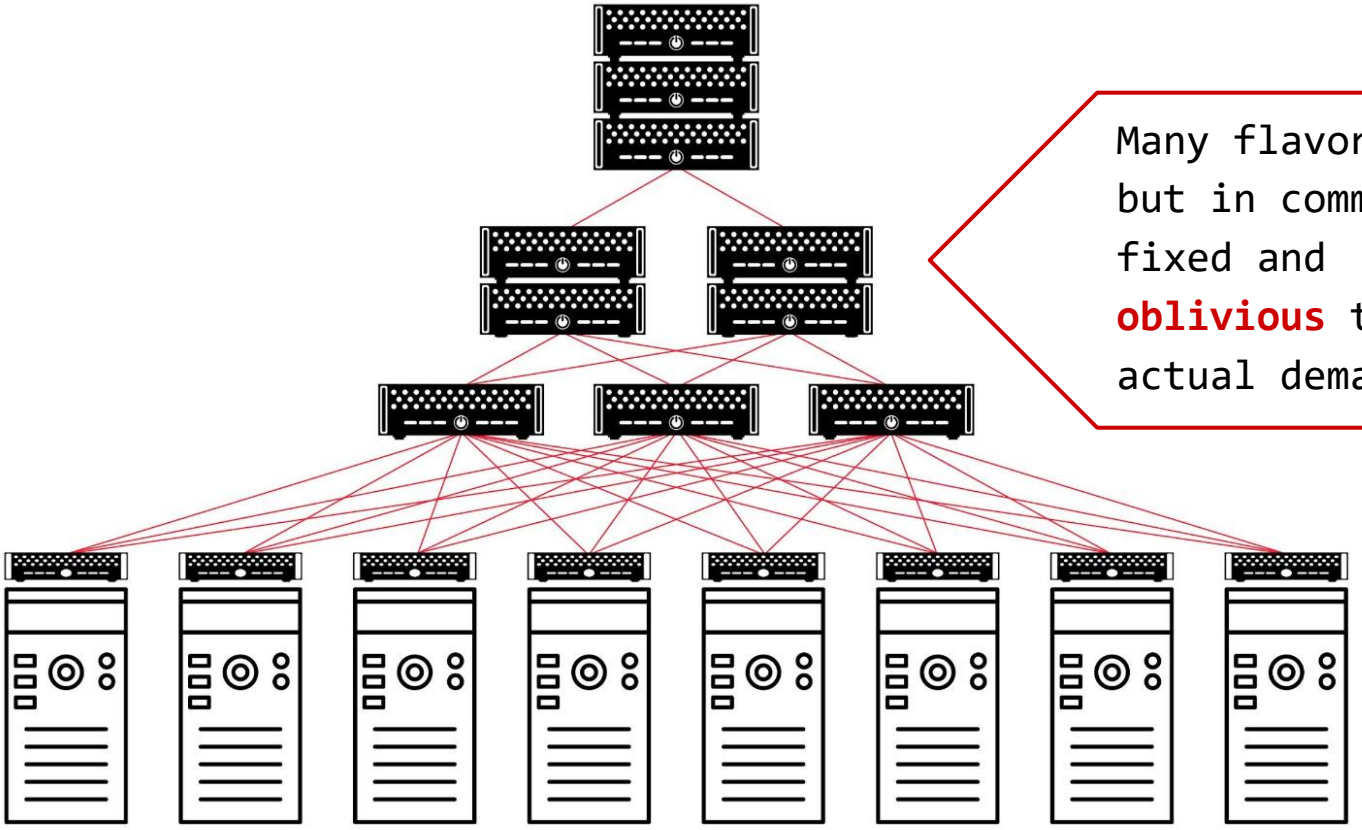
Fixed and Demand-Oblivious Topology

How to interconnect?



Root Cause

Fixed and Demand-Oblivious Topology



Many flavors, but in common: fixed and **oblivious** to actual demand.

Root Cause

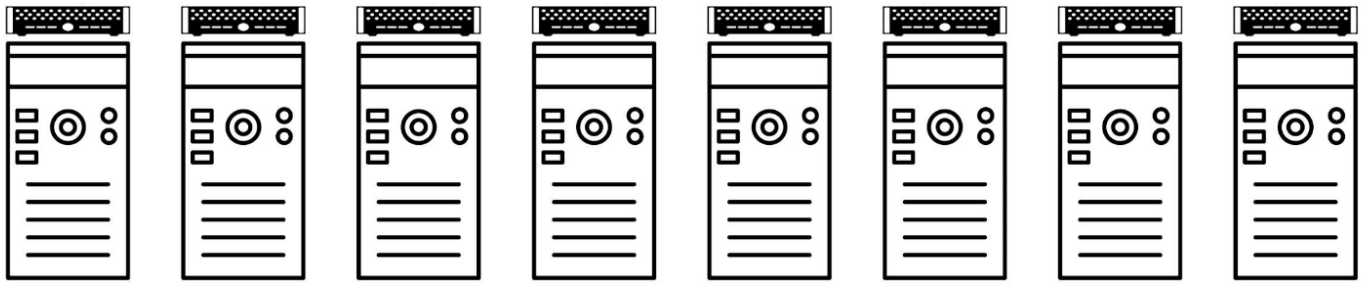
Fixed and Demand-Oblivious Topology

Highway which ignores actual traffic: frustrating!

Many flavors, but in common: fixed and **oblivious** to actual demand.

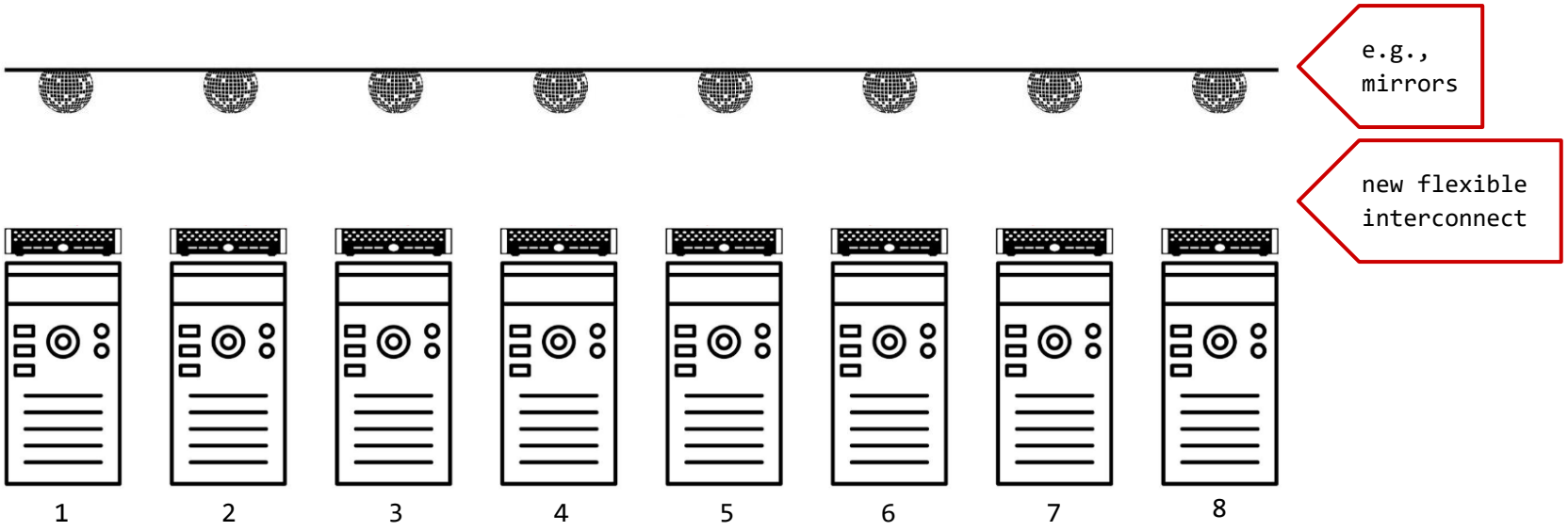
A Vision

Flexible and Demand-Aware Topologies



A Vision

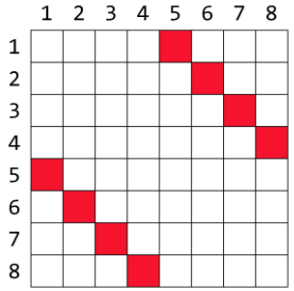
Flexible and Demand-Aware Topologies

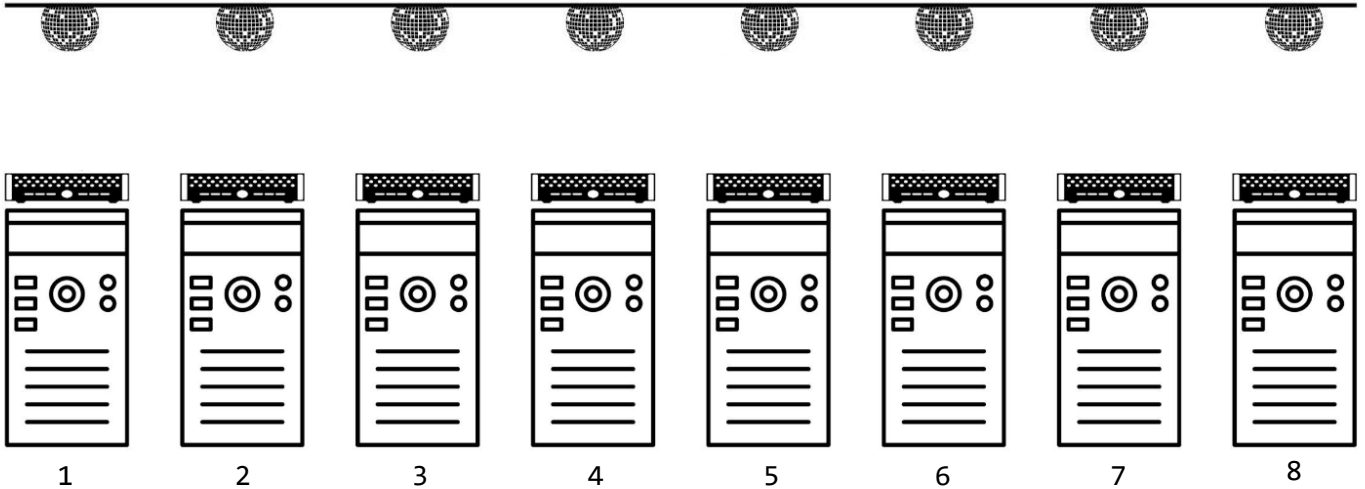


A Vision

Flexible and Demand-Aware Topologies

demand matrix:



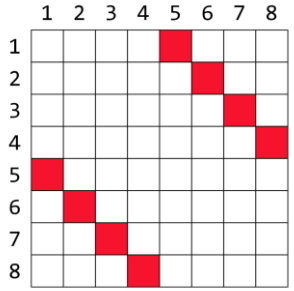


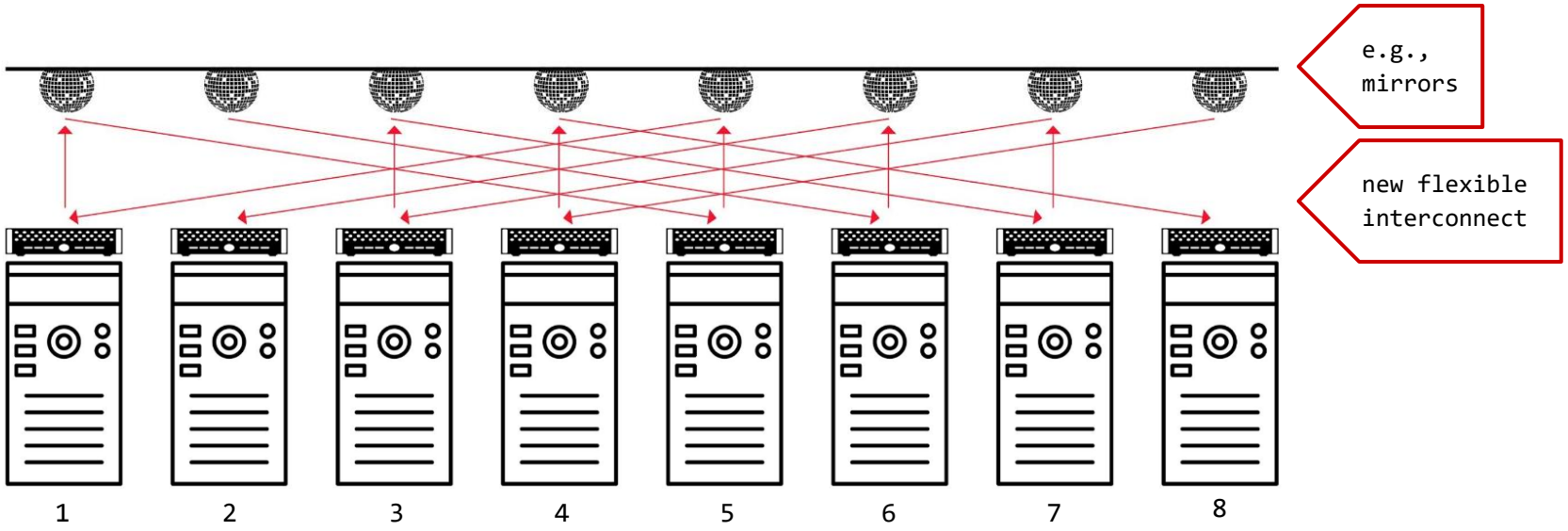
A Vision

Flexible and Demand-Aware Topologies

Matches demand

demand matrix:

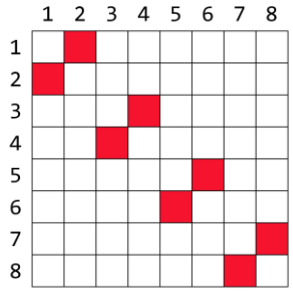


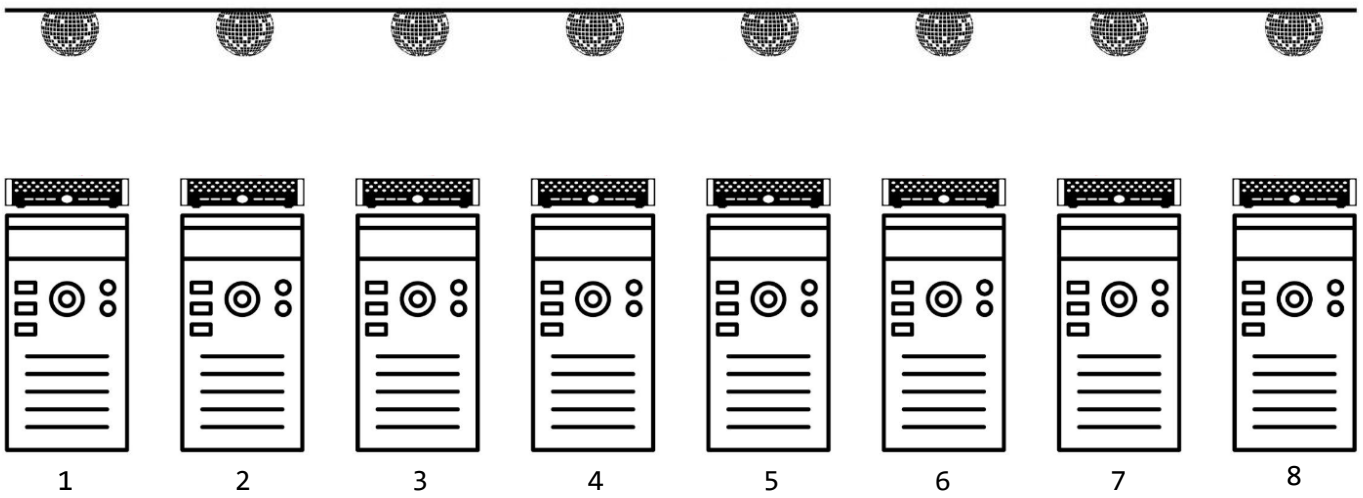


A Vision

Flexible and Demand-Aware Topologies

new demand:





A Vision

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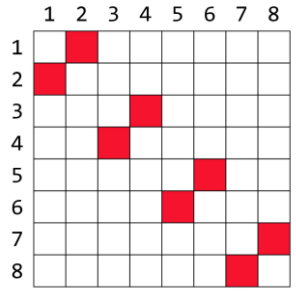
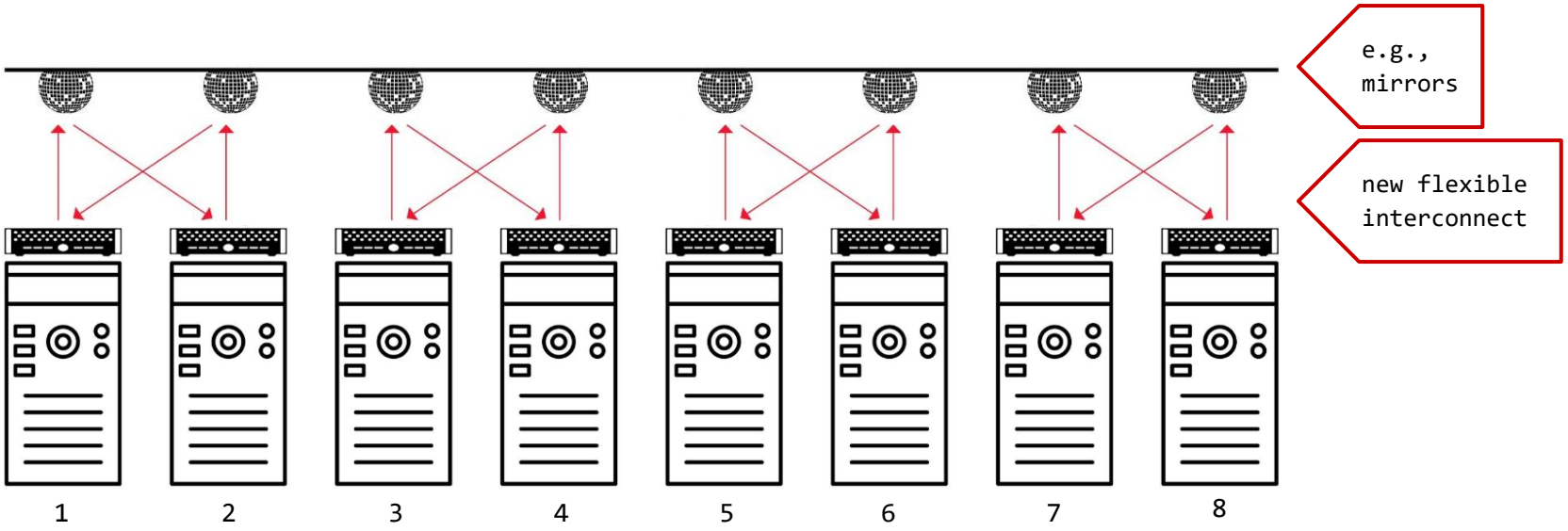


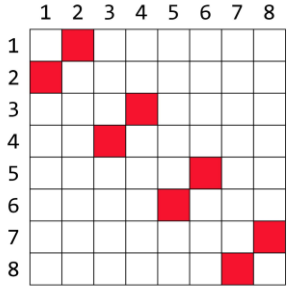


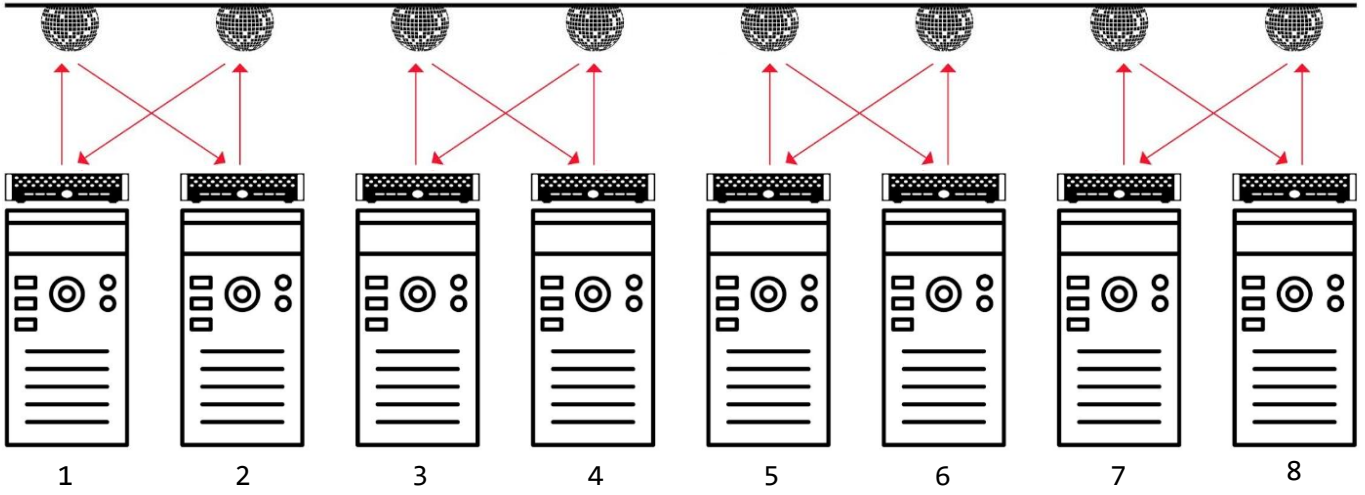
A Vision

Flexible and Demand-Aware Topologies

Demand-Aware Networks

new demand:



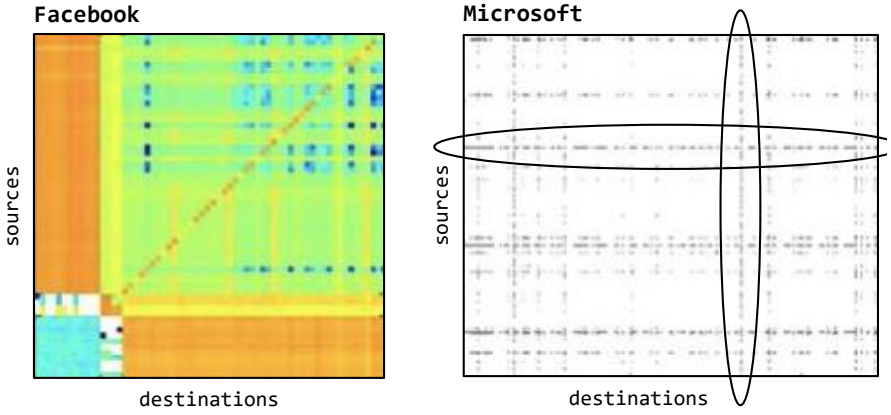


The Motivation

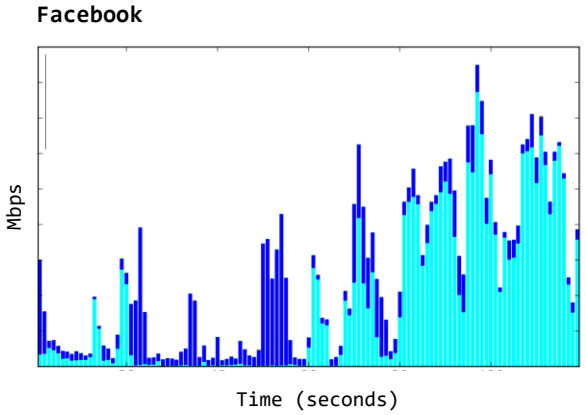
Much Structure in the Demand

Empirical studies:

traffic matrices sparse and skewed

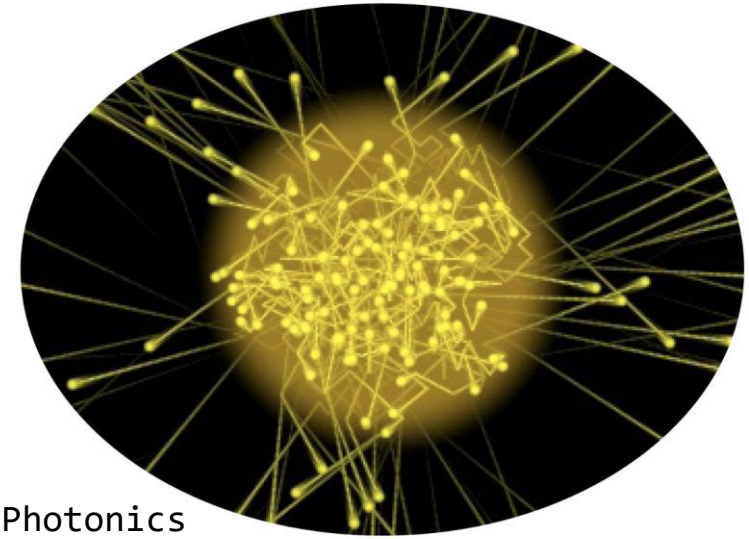


traffic bursty over time



Hypothesis: this can be exploited.

Sounds Crazy? Emerging Enabling Technology.



Photonics

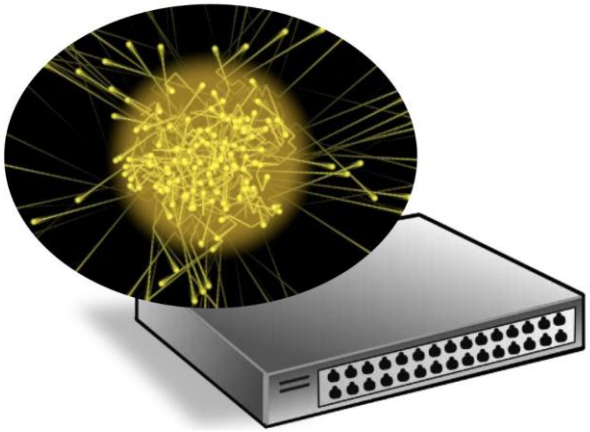
H2020:
“Photonics one of only five key enabling technologies for future prosperity.”

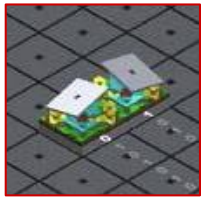
US National Research Council:
“Photons are the new Electrons.”

Enabler

Novel Reconfigurable Optical Switches

- **Spectrum** of prototypes
  - Different sizes, different reconfiguration times
  - From our last years' ACM **SIGCOMM** workshop OptSys





Prototype 1

Prototype 2

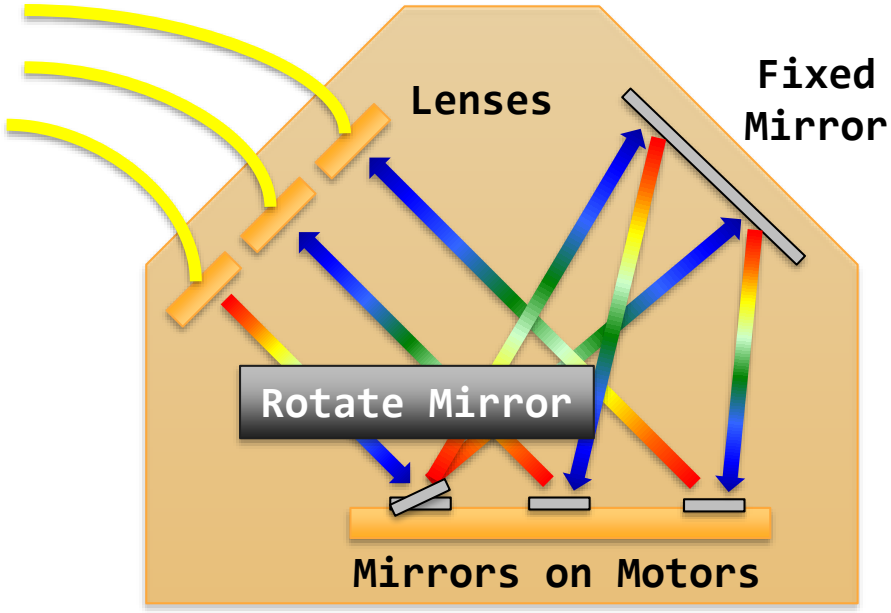
Prototype 3

Example

Optical Circuit Switch

⇢ Optical Circuit Switch rapid adaption of physical layer

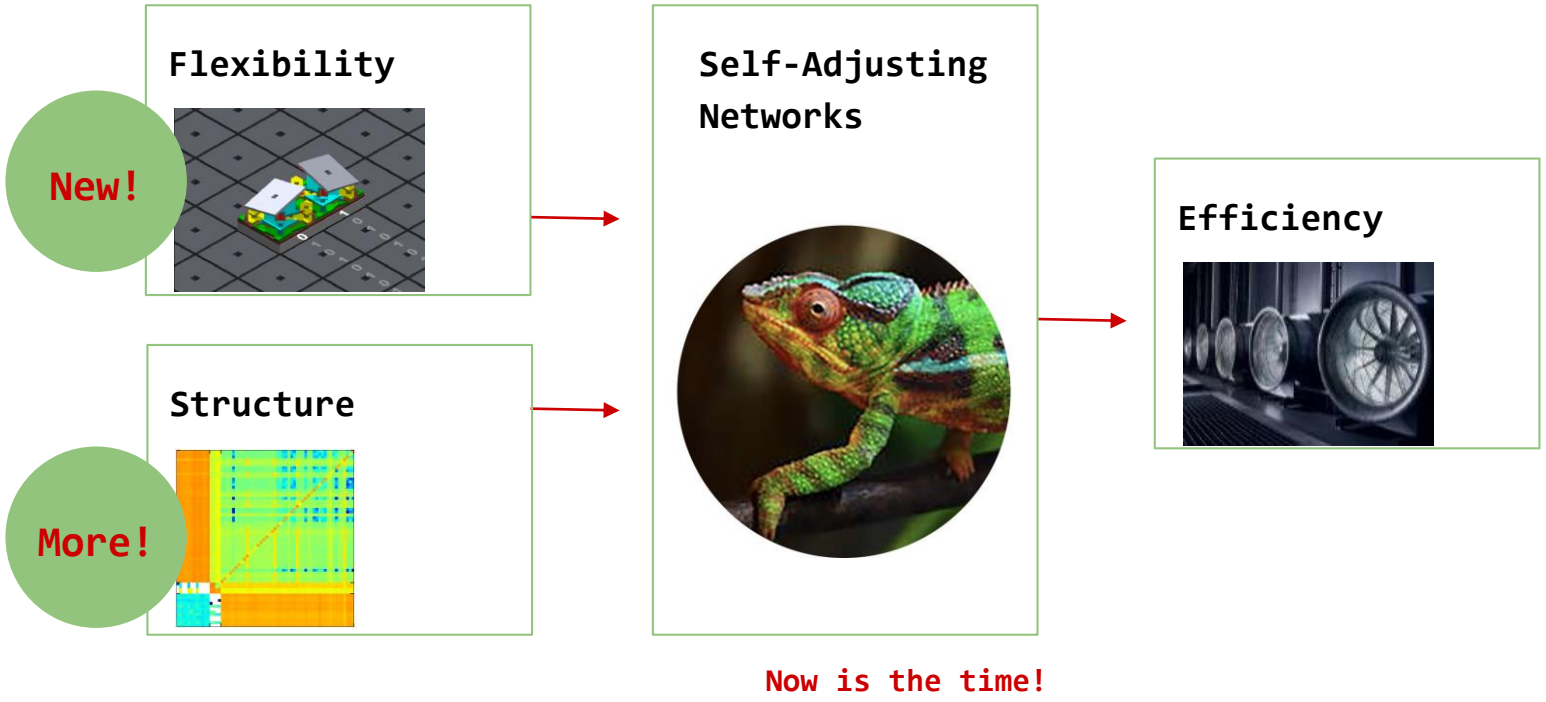
→ Based on rotating mirrors



Optical Circuit Switch

By Nathan Farrington, SIGCOMM 2010

The Big Picture



Unique Position

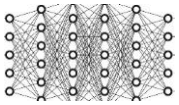
Demand-Aware, Self-Adjusting Systems

Everywhere, but mainly in software

Algorithmic trading

NETFLIX

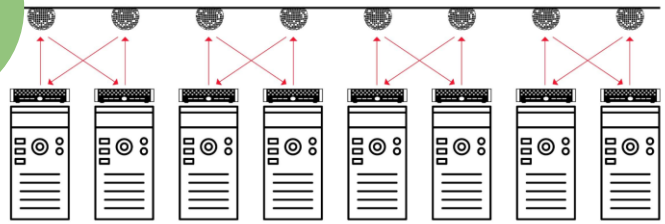
Recommender systems



Neural networks

VS

Our focus: in hardware

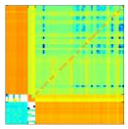


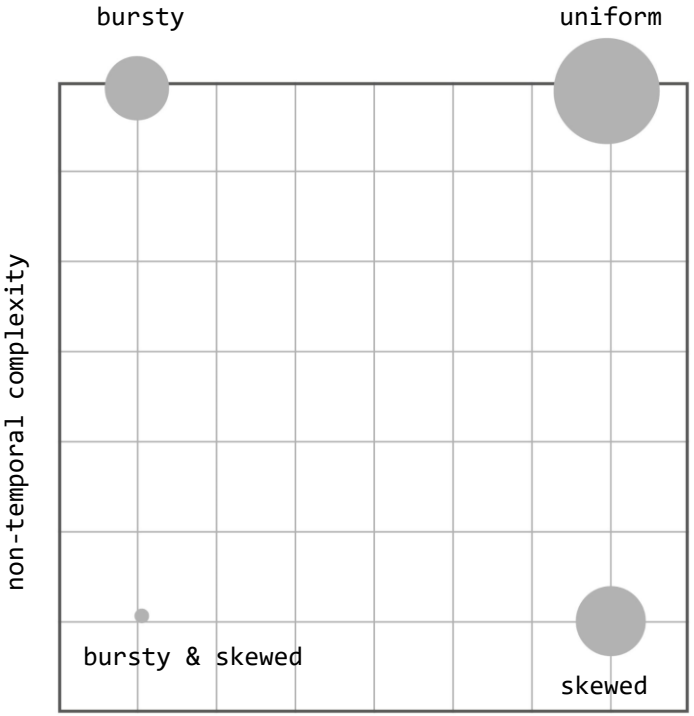
Question 1:

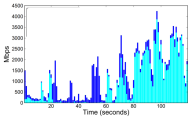
How to Quantify such “Structure” in the Demand?

An Information-Theoretic Approach

Complexity Map



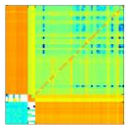


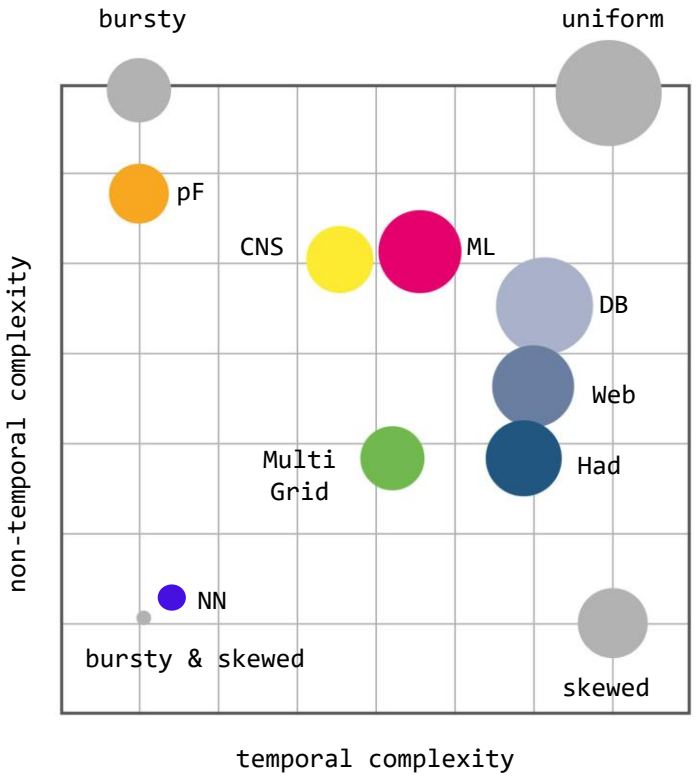


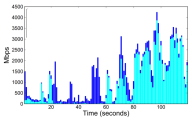
Our **approach**: iterative **randomization and compression** of trace to identify dimensions of structure.

An Information-Theoretic Approach

Complexity Map





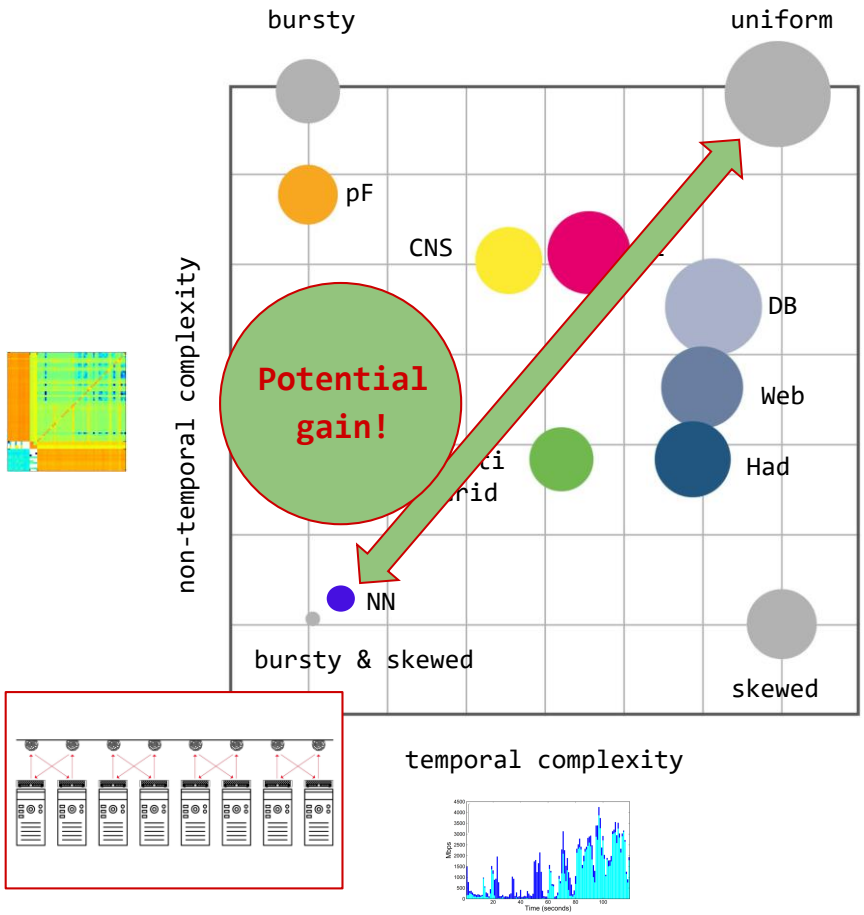


Our **approach**: iterative **randomization and compression** of trace to identify dimensions of structure.

Different structures!

An Information-Theoretic Approach

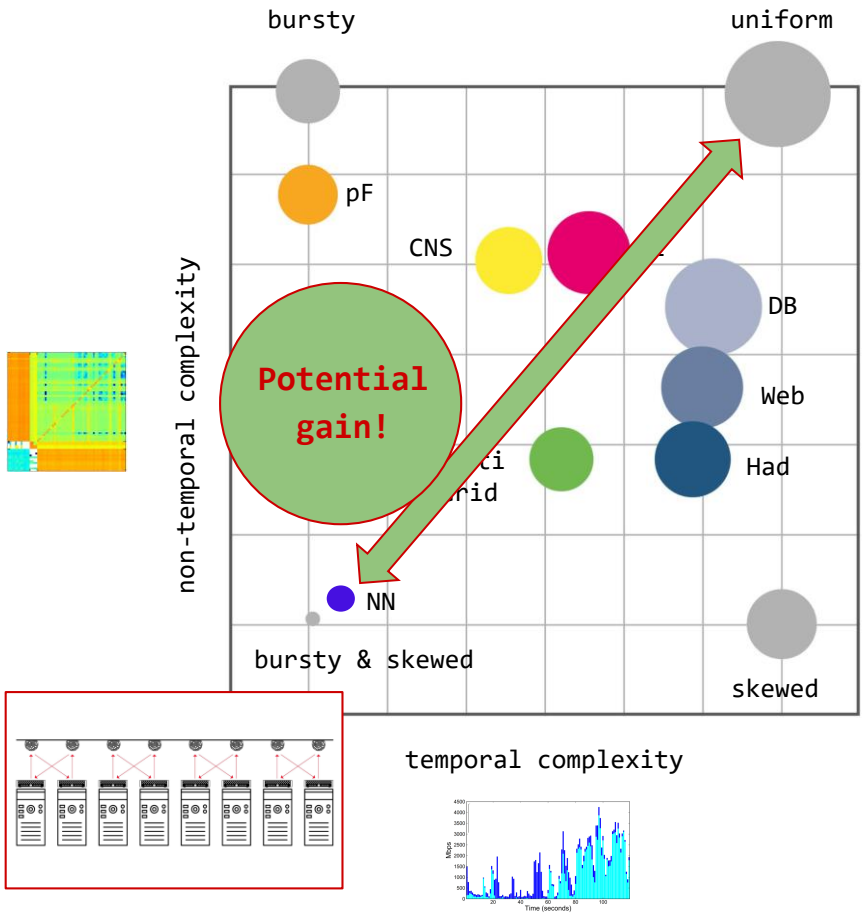
Complexity Map



Our **approach**: iterative **randomization and compression** of trace to identify dimensions of structure.

An Information-Theoretic Approach

Complexity Map



Our **approach**: iterative **randomization and compression** of trace to identify dimensions of structure.

Griner et al., Sigmetrics 2020

Question 2:

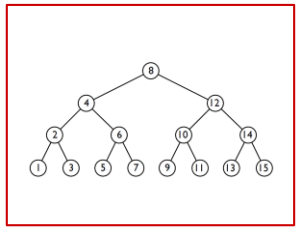
Given This Structure, What Can Be Achieved? Metrics and Algorithms?

A first insight: entropy of the demand.

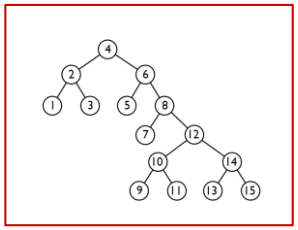
Interesting Perspective:

Connection to Datastructures

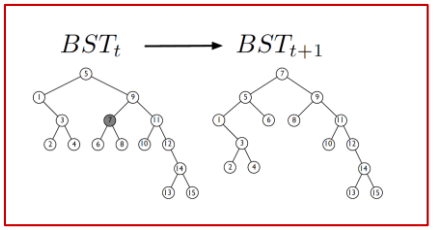
Traditional BST



Demand-aware BST



Self-adjusting BST



More structure: improved **access cost**

Interesting Perspective:

Connection to Datastructures & Coding

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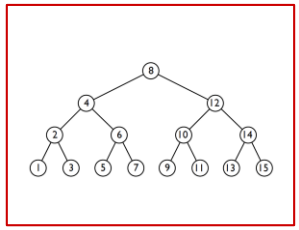

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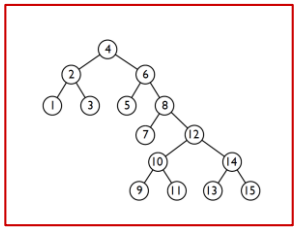

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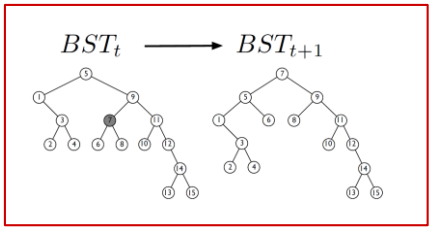

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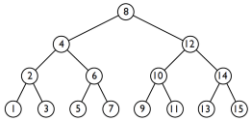

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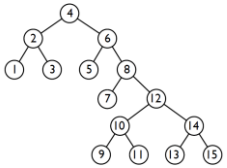

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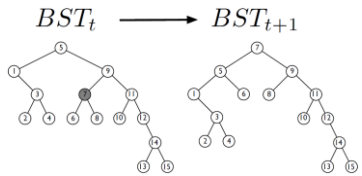

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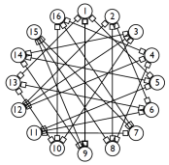

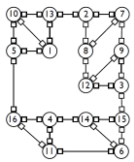

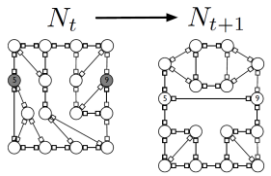

Similar **benefits**?

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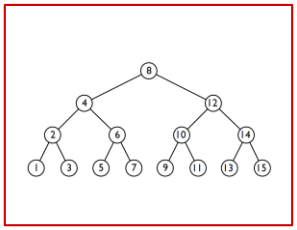

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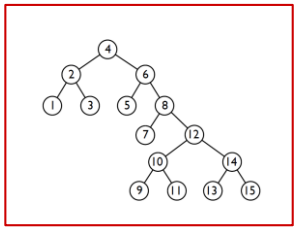

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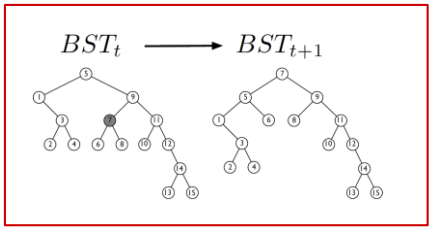

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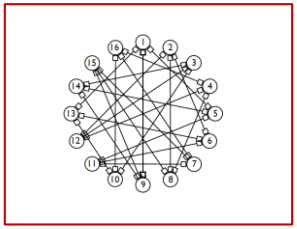

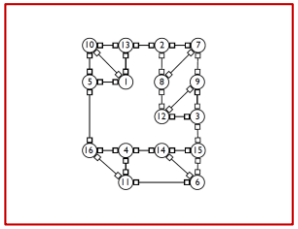

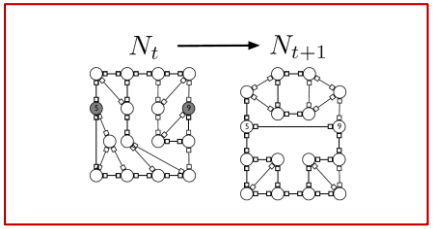

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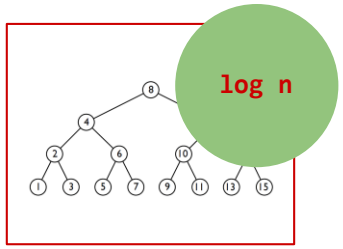

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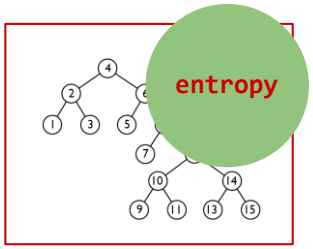

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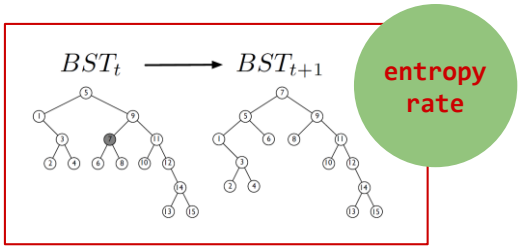

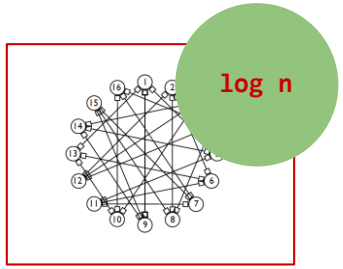

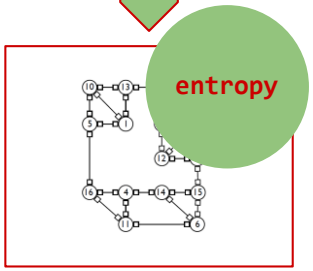

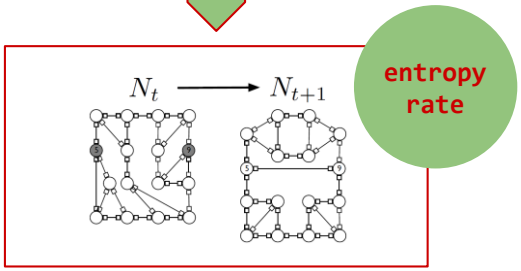

Reduced expected **route lengths**!

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Generalize methodology:
... and transfer entropy bounds and algorithms of data-structures to networks.

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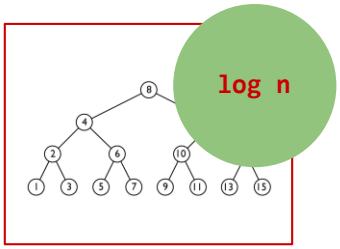

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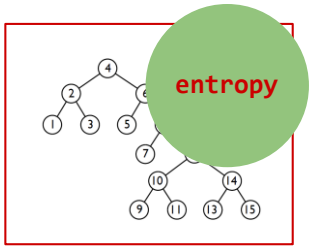

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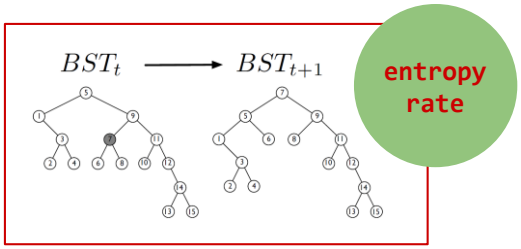

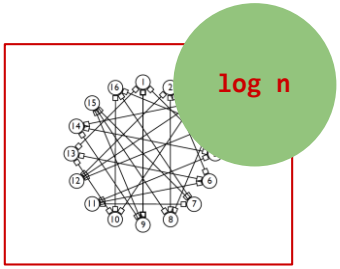

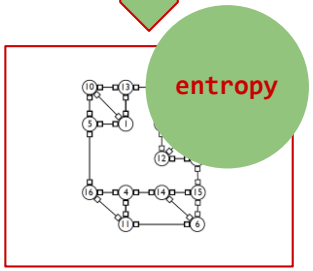

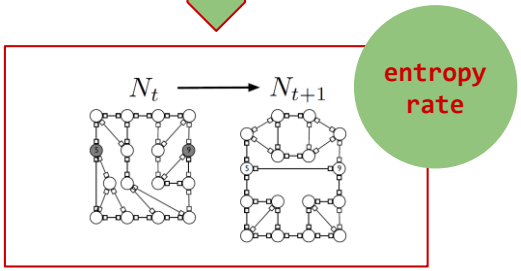

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Avin et al., SIGCOMM CCR 2018.

Agenda

Three Use Cases

Passau, Germany

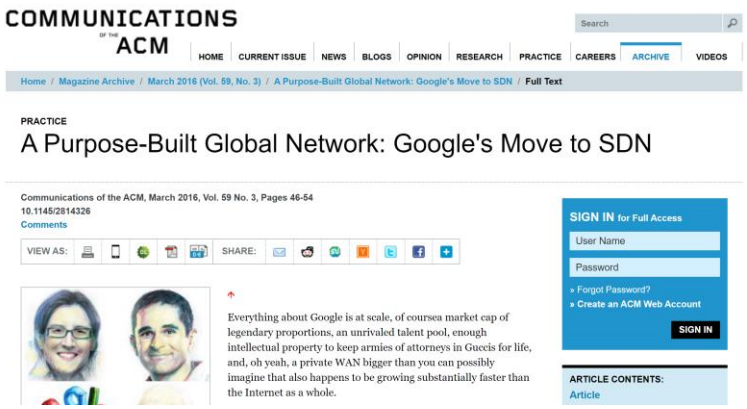
Another Benefit of Automation:

More Adaptive Operation

⇢ Automation and programmability: enables more **adaptable networks**

⇢ Attractive for:

- ⇢ Fine-grained traffic engineering (e.g., at Google)
- ⇢ Accounting for changes in the demand (spatio-temporal structure)
- ⇢ Security policy changes
- ⇢ Service relocation
- ⇢ Maintenance work
- ⇢ Link/node failures



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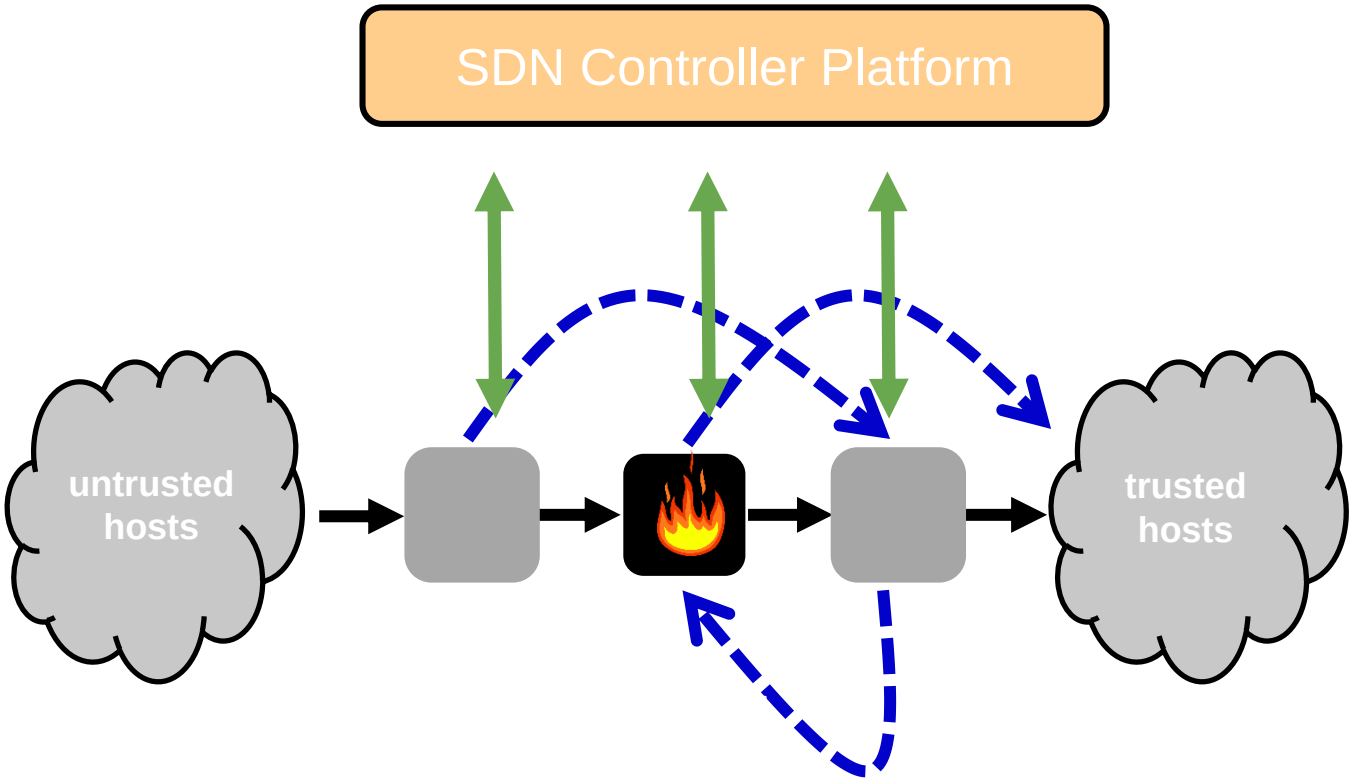

Enabled by SDN, it has become „easy“ to quickly change route to blue route.

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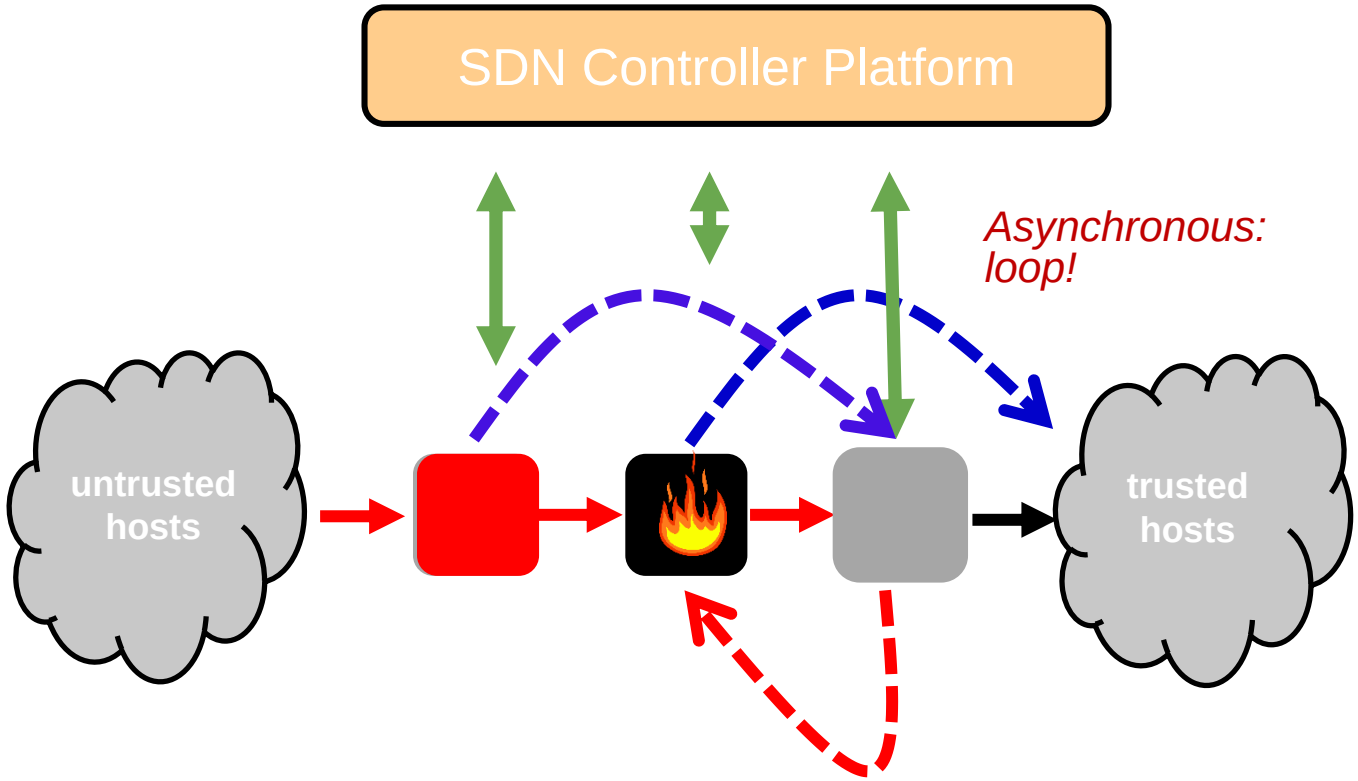

But still need clever algorithms! Updates are asynchronous, may lead to temporal inconsistencies.

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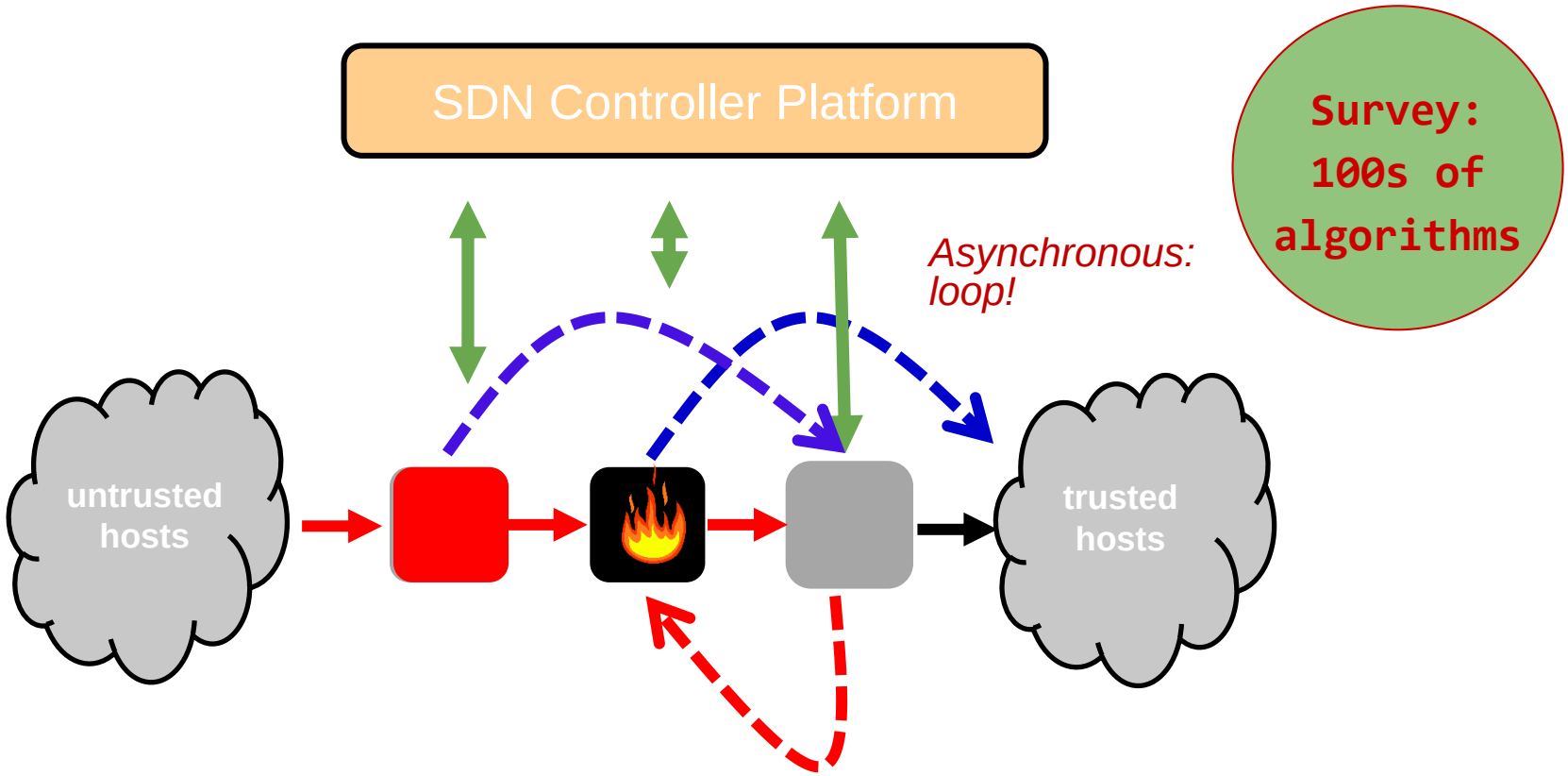

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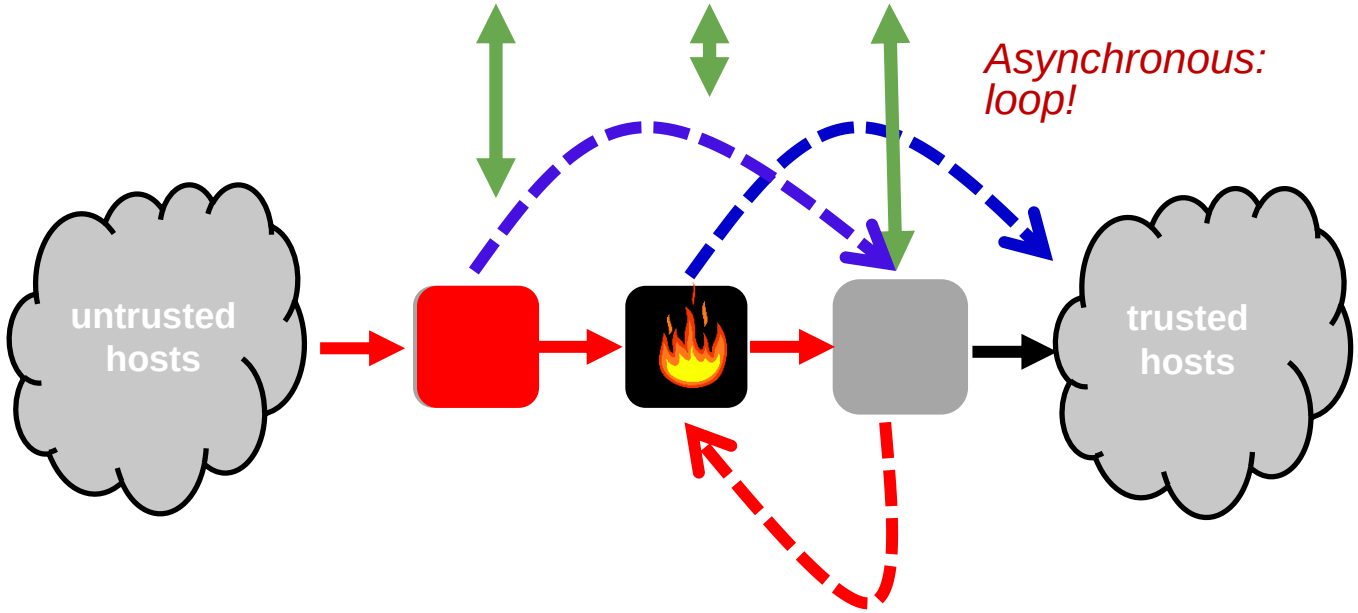
Again: Formal Methods for

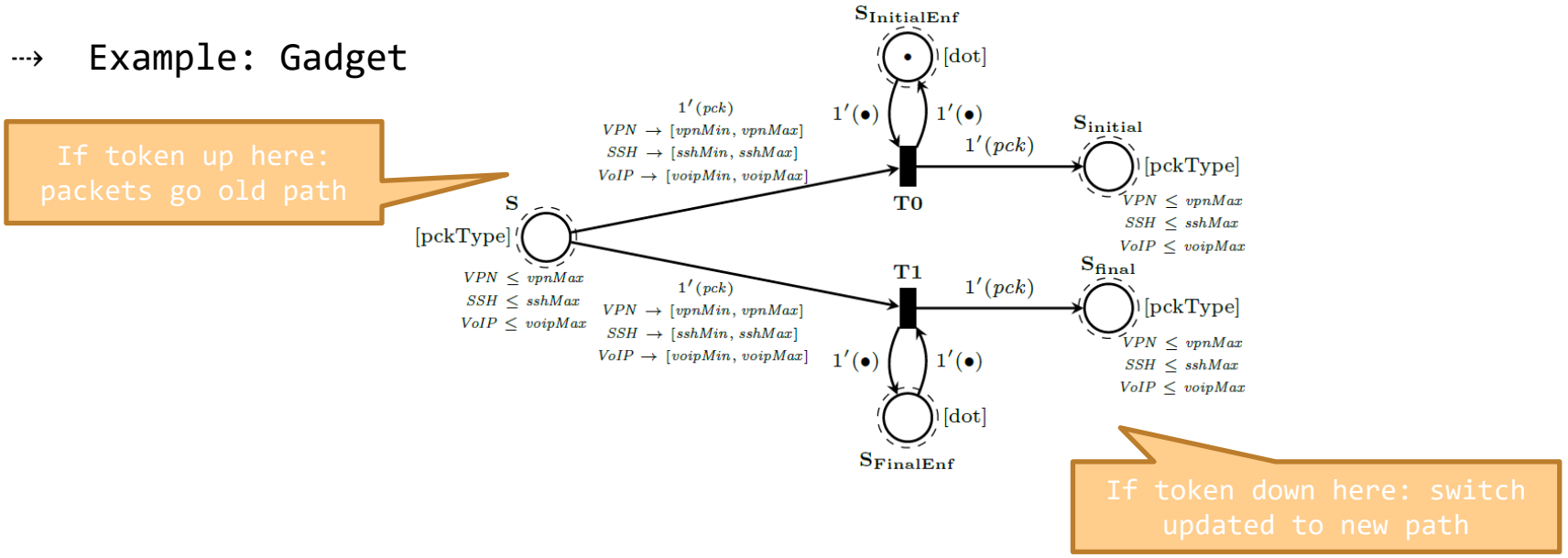
Self-Adjusting Updates



Vision: self-adjusting networks could synthesize even their algorithms! „Ex machina“: e.g., parametrized.

Examples: NetSynth, Latte

- Already "*in the making*"!
- NetSynth (PLDI'15): supports **any LTL property** and hence **operator preferences**. Then: standard framework to synthesize schedule.
- Latte (PER'20): fast Petri net model and ***synthesis***
- Example: Gadget



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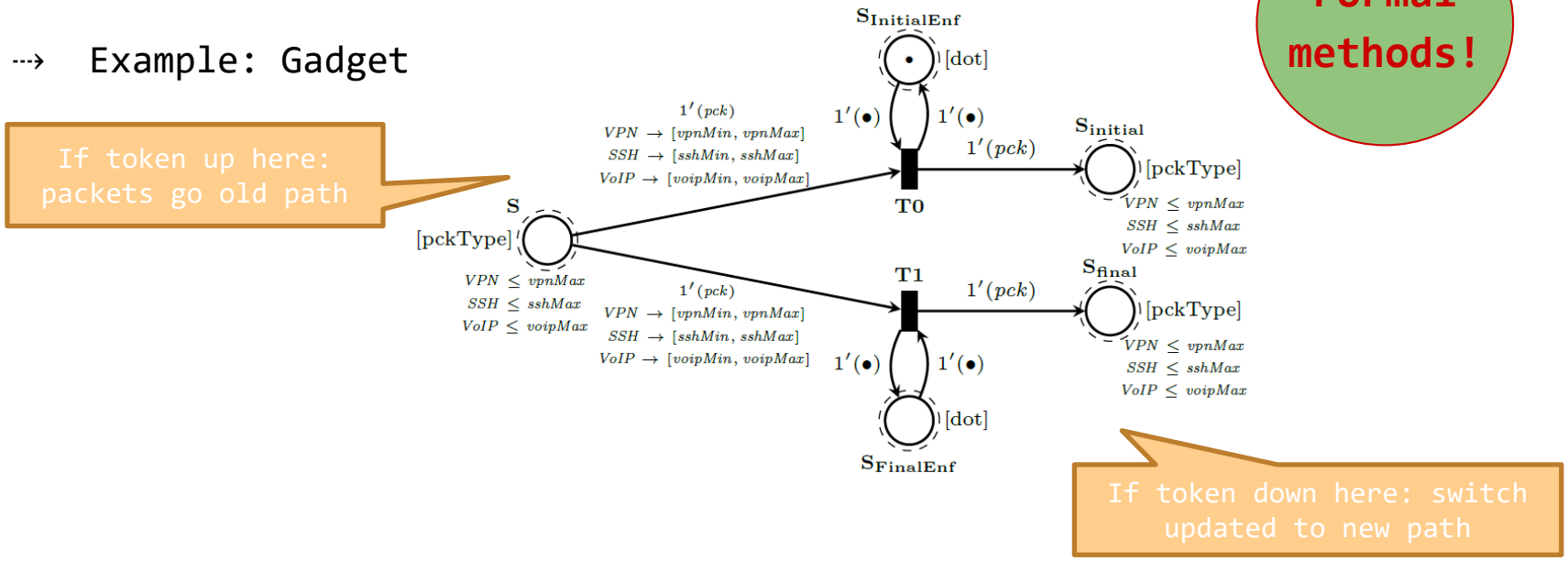

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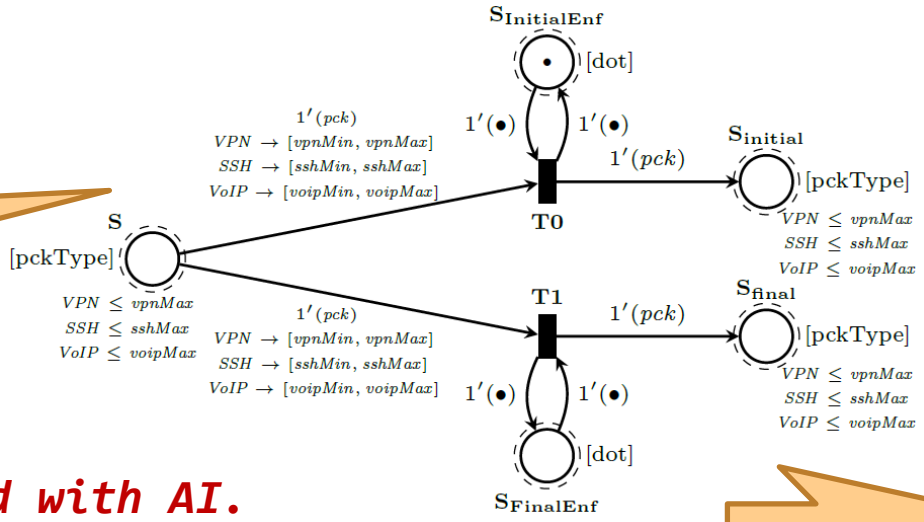
Formal methods!

If token up here: packets go old path



If token down here: switch updated to new path

May be enhanced with AI.

Challenges of Self-Adjusting Networks

Challenges

⇢ ***Performance*** of formal methods? Opportunity: ***algorithm engineering***!

⇢ Use of ***AI***: to speed up synthesis and deal with complexity?

⇢ Limitations of automation: can networks detect themselves, when the need “help from the operator”?

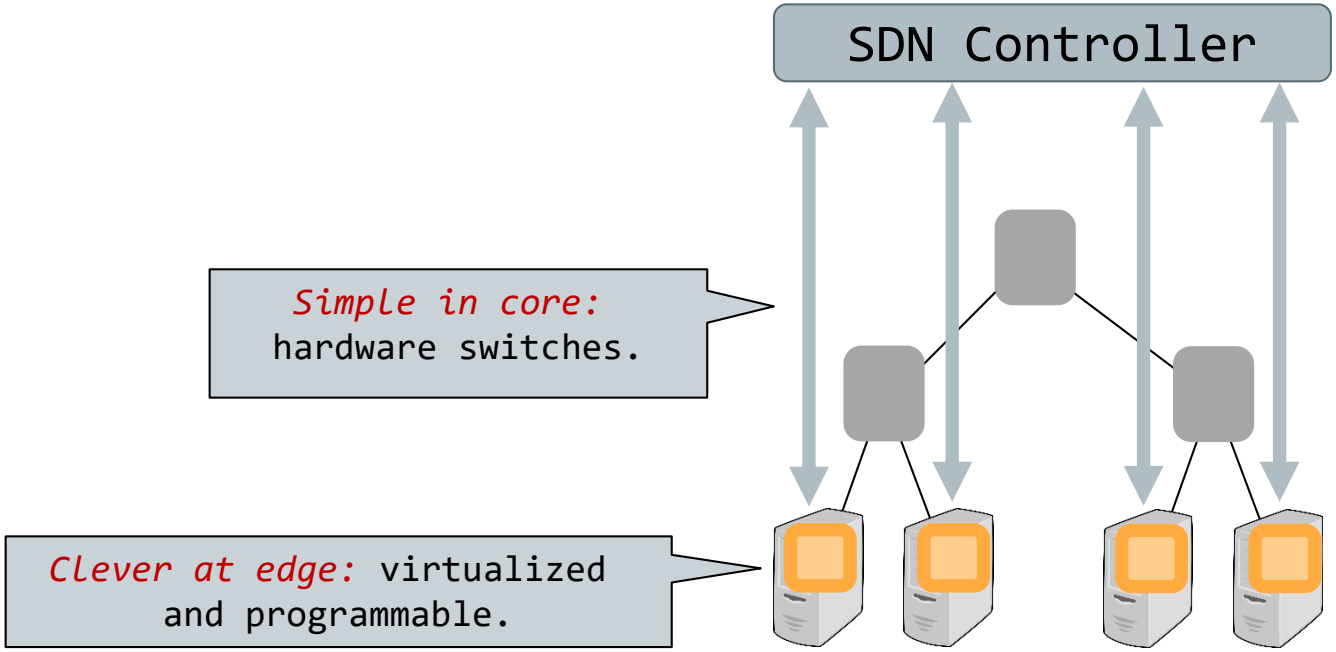
⇢ ***Data:*** How to learn about and/or predict demand? Telemetry?

⇢ Programmability vs ***security***?

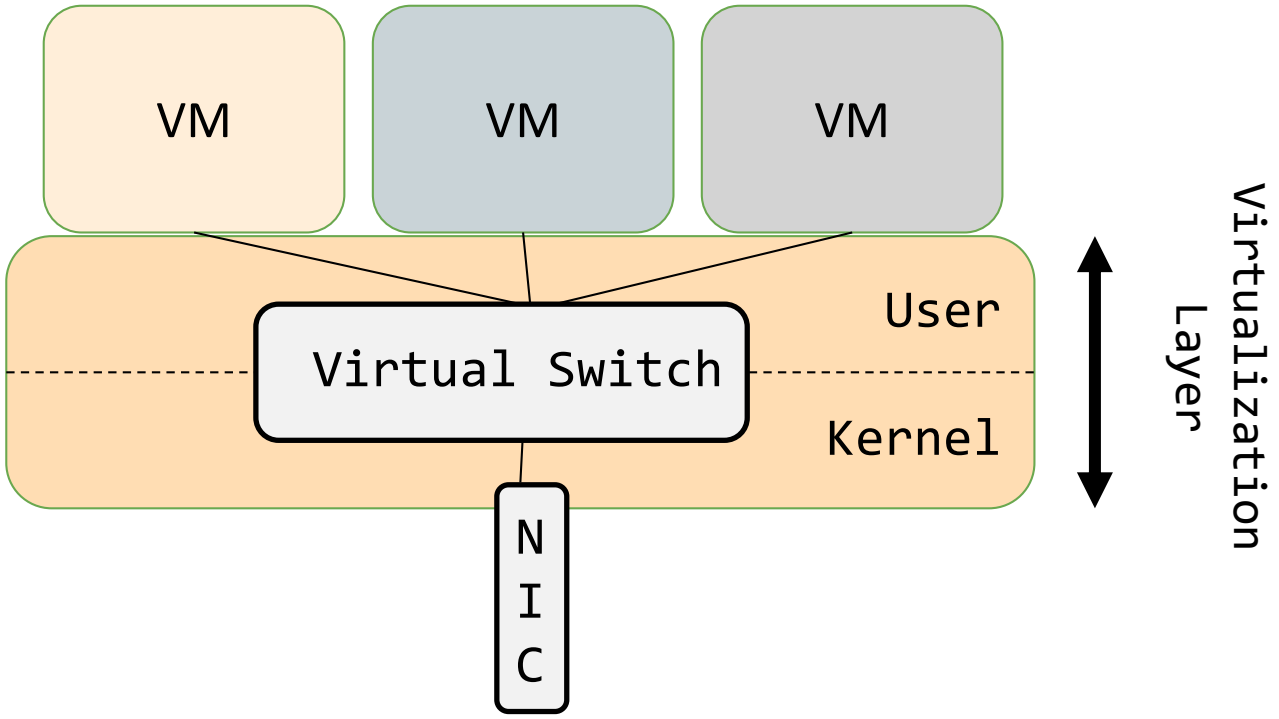
Example: Security

⇢ Enabling technology like SDN often deployed "*in software*"

⇢ E.g., virtual switches in datacenters



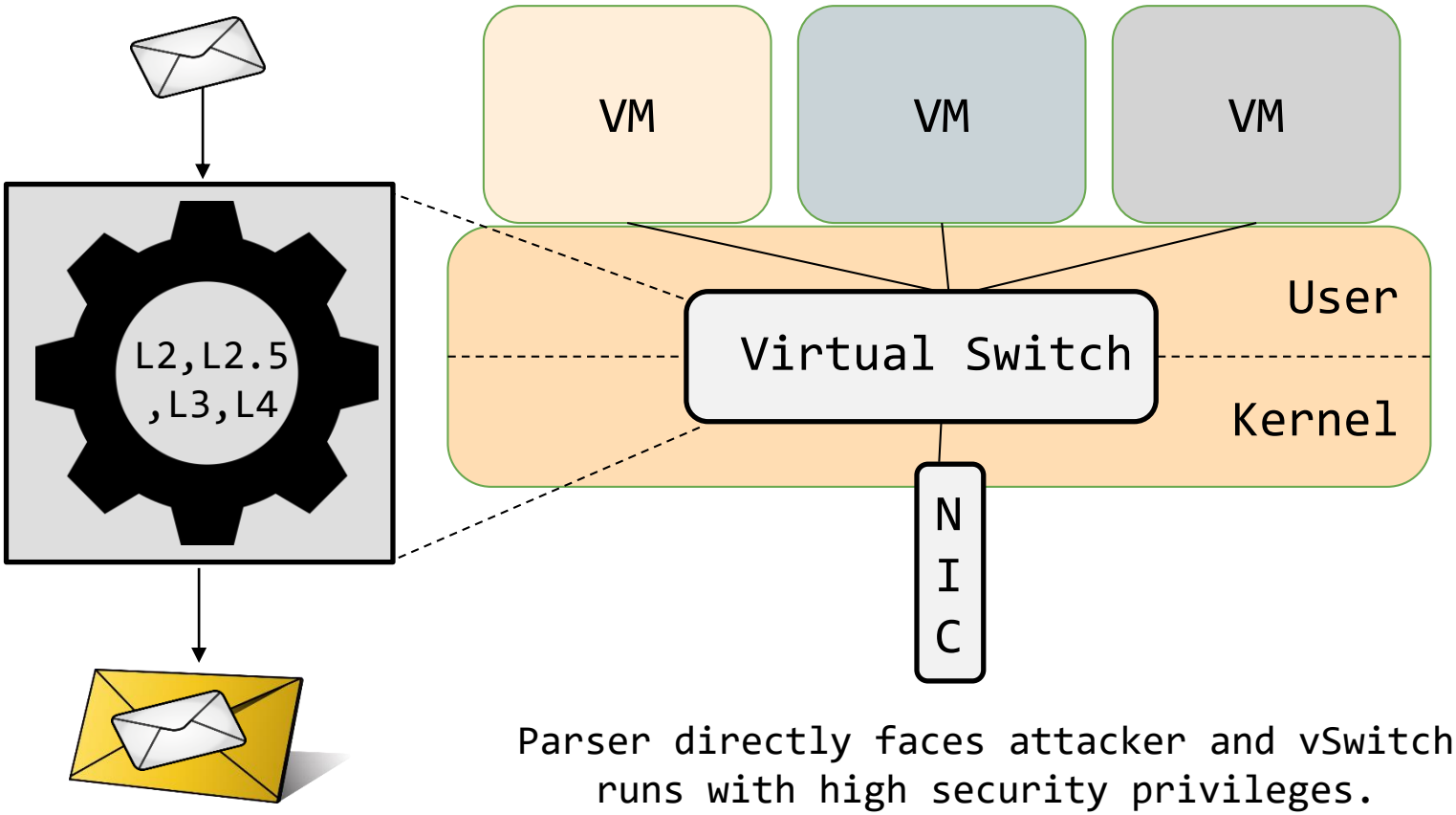
Virtual Switches



Virtual switches reside in the **server's virtualization layer** (e.g., Xen's Dom0).
Goal: provide connectivity and isolation.

Complexity: Parsing

Ethernet
LLC
VLAN
MPLS
IPv4
ICMPv4
TCP
UDP
ARP
SCTP
IPv6
ICMPv6
IPv6 ND
GRE
LISP
VXLAN
PBB
IPv6 EXT HDR
TUNNEL-ID
IPv6 ND
IPv6 EXT HDR
IPv6HOPOPTS
IPv6ROUTING
IPv6Fragment
IPv6DESTOPT
IPv6ESP
IPv6 AH
RARP
IGMP



Parser directly faces attacker and vSwitch runs with high security privileges.

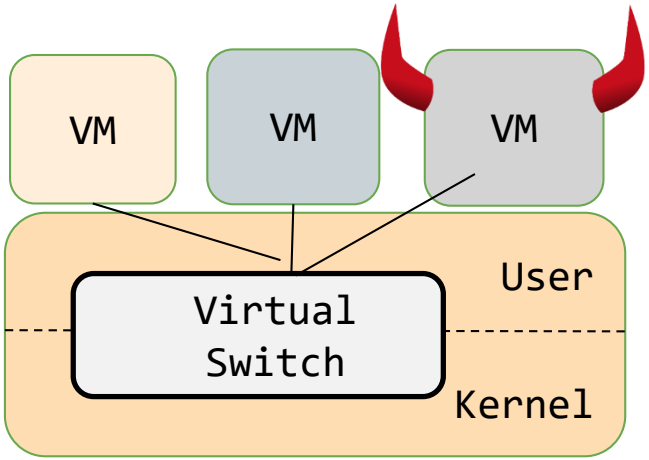
Parsing must be fast!

Unified packet parser is fast, but complex.

Credits:

Marco Chiesa

Bears Risks!



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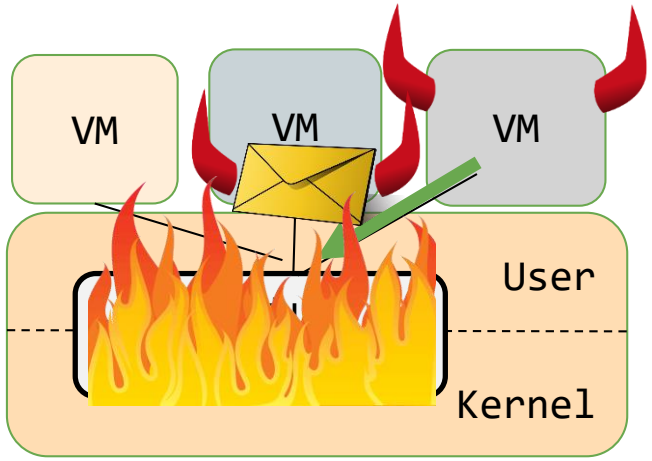

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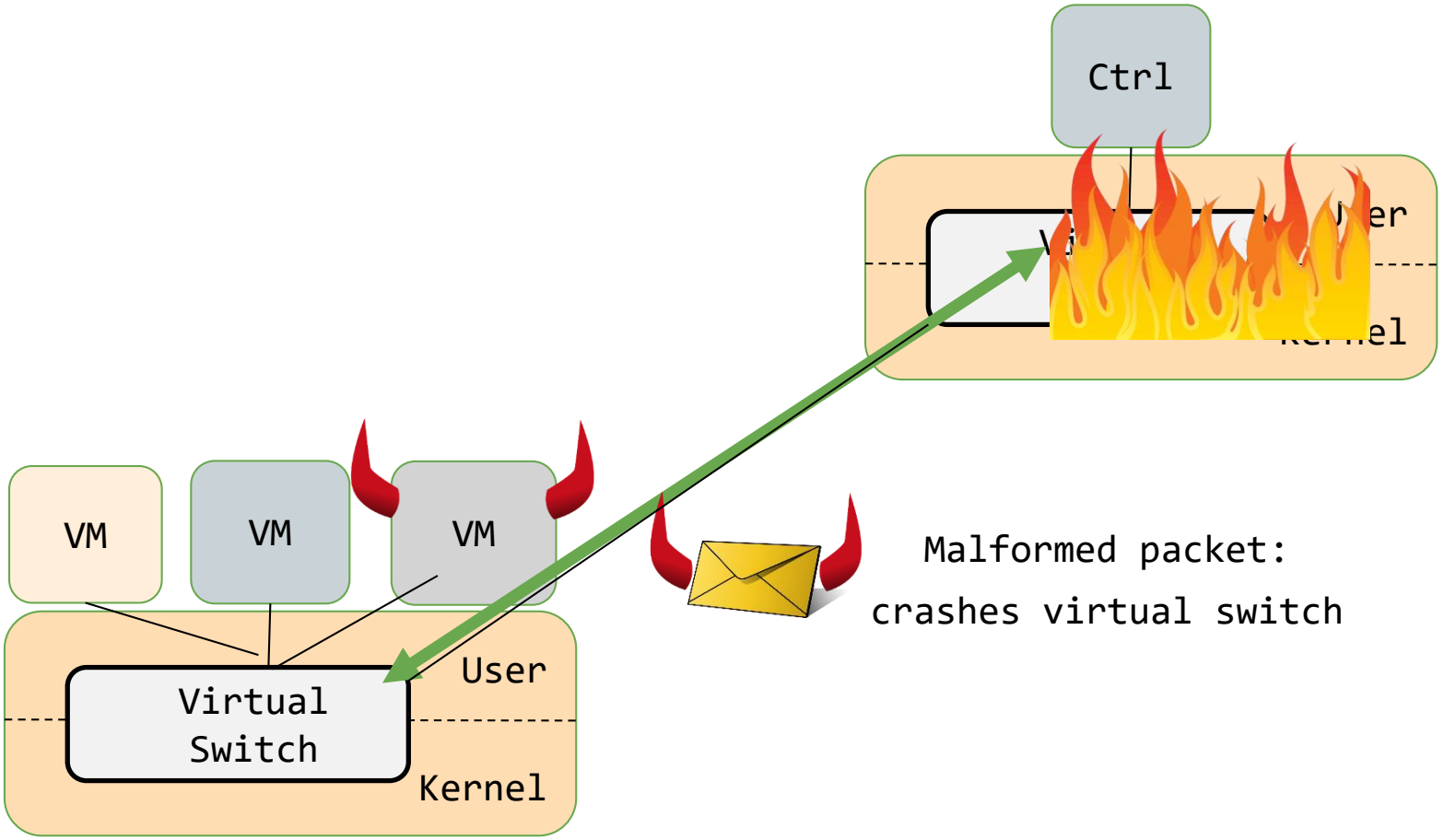
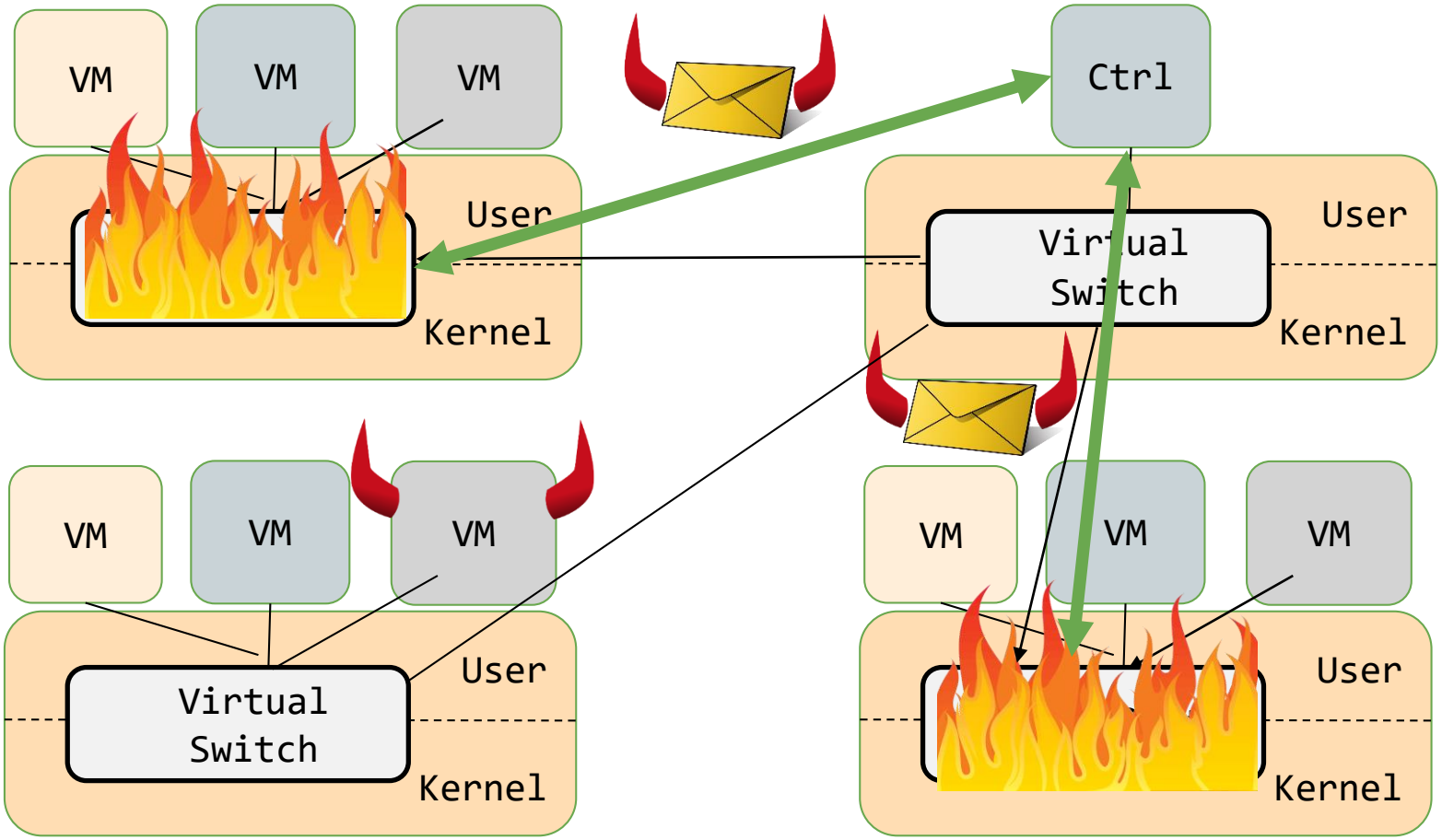

Ctrl
VM
VM
VM
User
Virtual
Switch
Kernel
Malformed packet:
crashes virtual switch

Bears Risks!


VM
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User
Kernel
Ctrl
User
Virtual Switch
Kernel
VM
VM
VM
User
Virtual Switch
Kernel
VM
VM
VM
User
Kernel

Conclusion

⇢ A vision: self-adjusting networks

⇢ Example 1: policy-compliant networks

- ⇀ self-verifying
- ⇀ self-repairing

⇢ Example 2: demand-aware topologies

⇢ On both fronts: tip of the iceberg!

⇀ E.g., self-adjusting networks further supported by telemetry (data) and AI (e.g., prediction)

Thank you!

References

AalWiNes: A Fast and Quantitative What-If Analysis Tool for MPLS Networks
Peter Gjøl Jensen, Morten Konggaard, Dan Kristiansen, Stefan Schmid, Bernhard Clemens Schrenk, and Jiri Srba.
16th ACM International Conference on emerging Networking EXperiments and Technologies (**CoNEXT**), Barcelona, Spain, December 2020.

On the Complexity of Traffic Traces and Implications
Chen Avin, Manya Ghobadi, Chen Griner, and Stefan Schmid.
ACM **SIGMETRICS** and ACM Performance Evaluation Review (**PER**), Boston, Massachusetts, USA, June 2020.

Toward Demand-Aware Networking: A Theory for Self-Adjusting Networks (Editorial)
Chen Avin and Stefan Schmid.
ACM SIGCOMM Computer Communication Review (**CCR**), October 2018.

Cerberus: The Power of Choices in Datacenter Topology Design (A Throughput Perspective)
Chen Griner, Johannes Zerwas, Andreas Blenk, Manya Ghobadi, Stefan Schmid, and Chen Avin.
ACM **SIGMETRICS** and ACM Performance Evaluation Review (**PER**), Mumbai, India, June 2022.

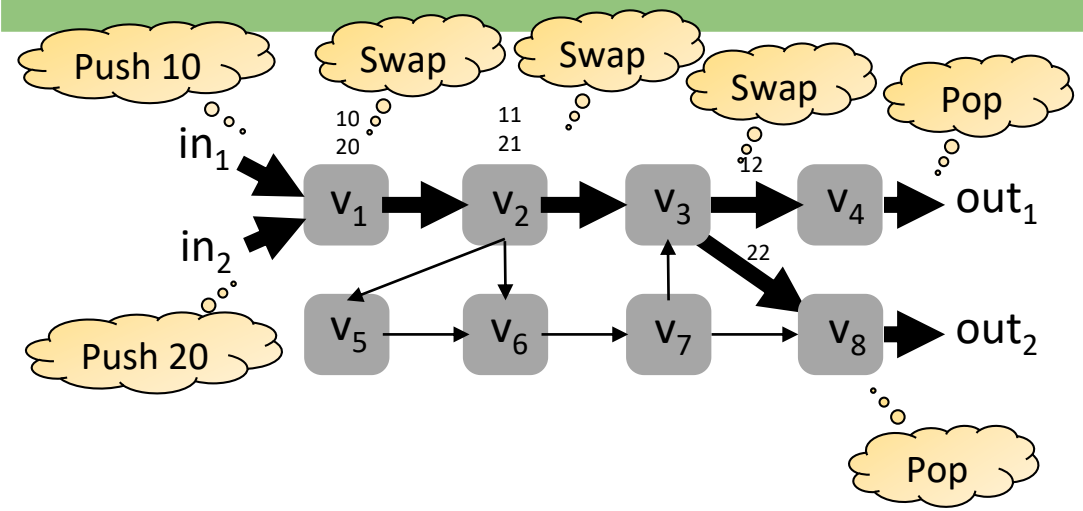
Latte: Improving the Latency of Transiently Consistent Network Update Schedules
Mark Glavind, Niels Christensen, Jiri Srba, and Stefan Schmid.
38th International Symposium on Computer Performance, Modeling, Measurements and Evaluation (**PERFORMANCE**) and ACM Performance Evaluation Review (**PER**), Milan, Italy, November 2020.

Taking Control of SDN-based Cloud Systems via the Data Plane (Best Paper Award)
Kashyap Thimmaraju, Bhargava Shastry, Tobias Fiebig, Felicitas Hetzelt, Jean-Pierre Seifert, Anja Feldmann, and Stefan Schmid.
ACM Symposium on SDN Research (**SOSR**), Los Angeles, California, USA, March 2018.

Backup Slides

Case Study:

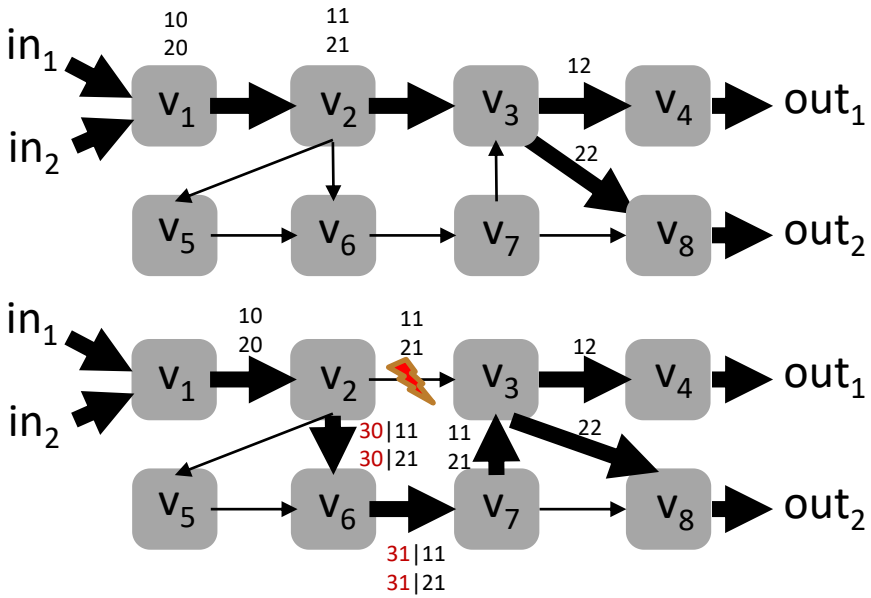
MPLS Networks



Original Routing

Case Study:

MPLS Networks

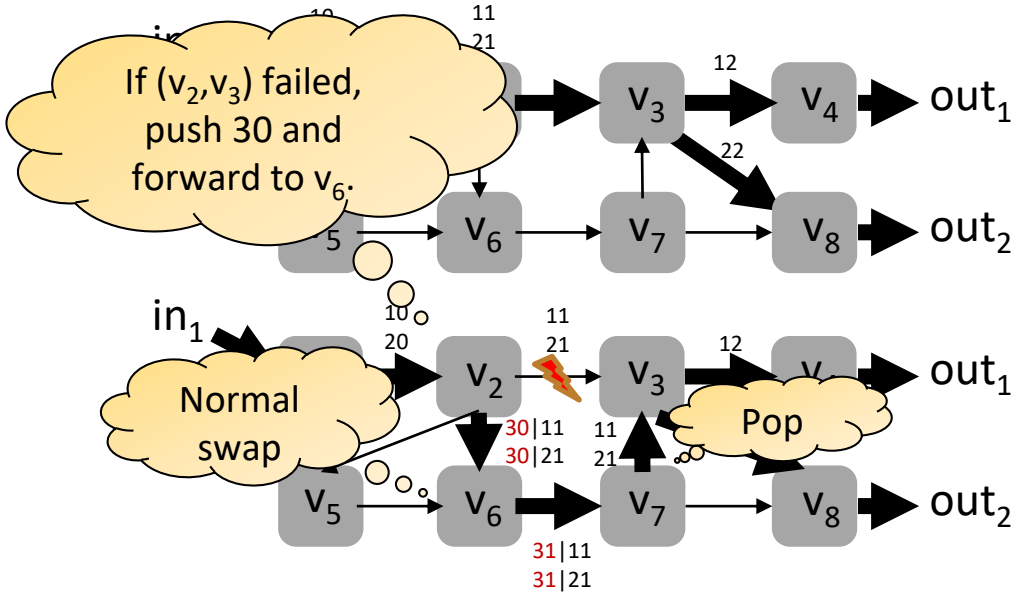


Original Routing

One failure: push 30: route around (v_2, v_3)

Case Study:

MPLS Networks



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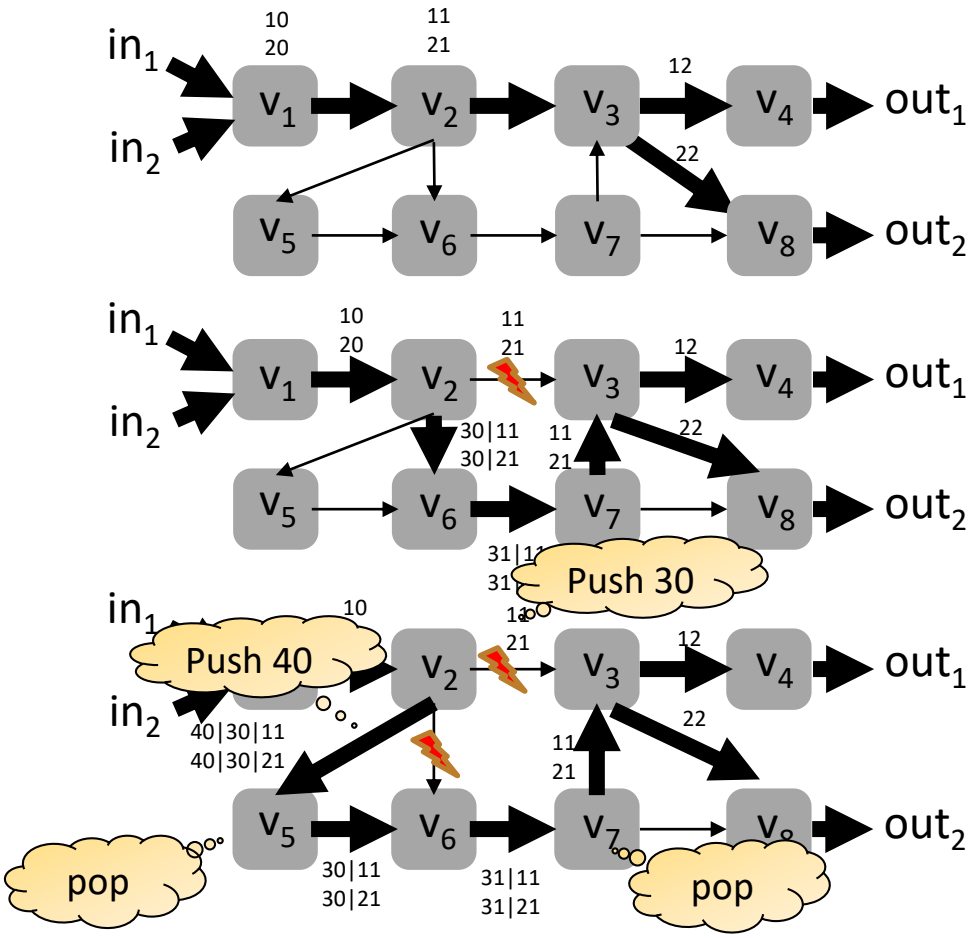


Original Routing

One failure: push 30: route around (v_2,v_3)

Two failures: first push 30: route around (v_2,v_3)

Push recursively

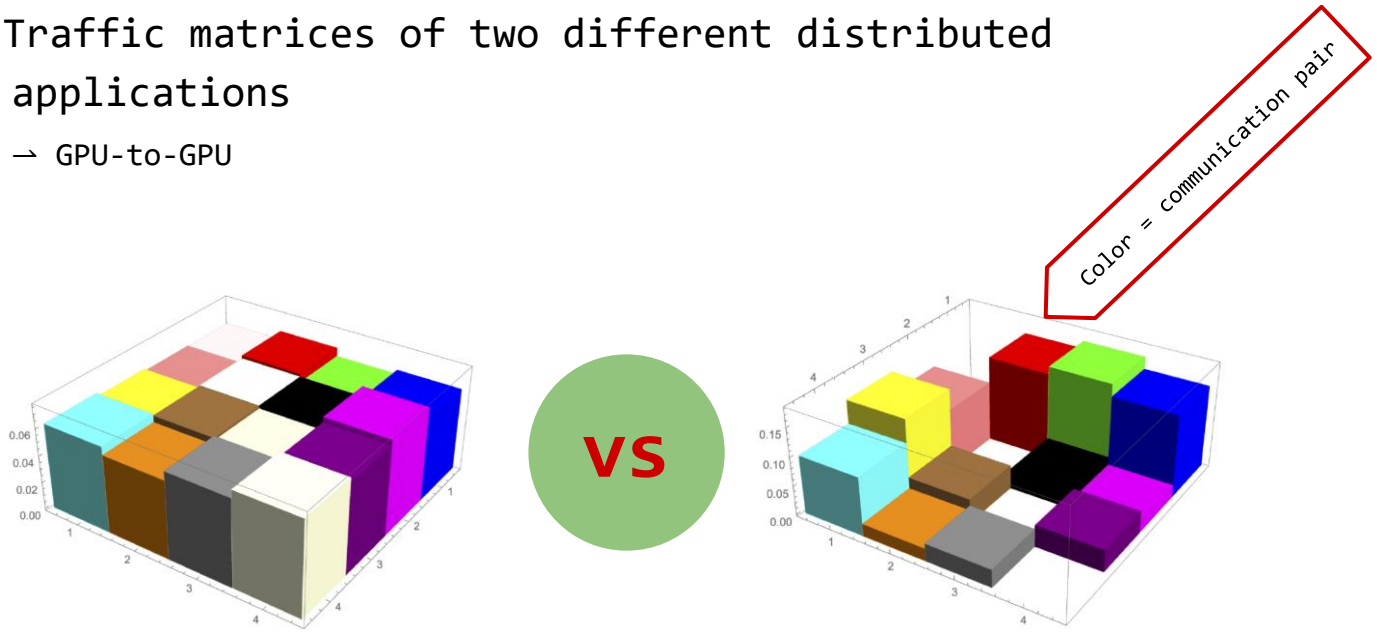
40: route around (v_2,v_6)

Intuition

Which demand has more structure?

⇢ Traffic matrices of two different distributed ML applications

→ GPU-to-GPU

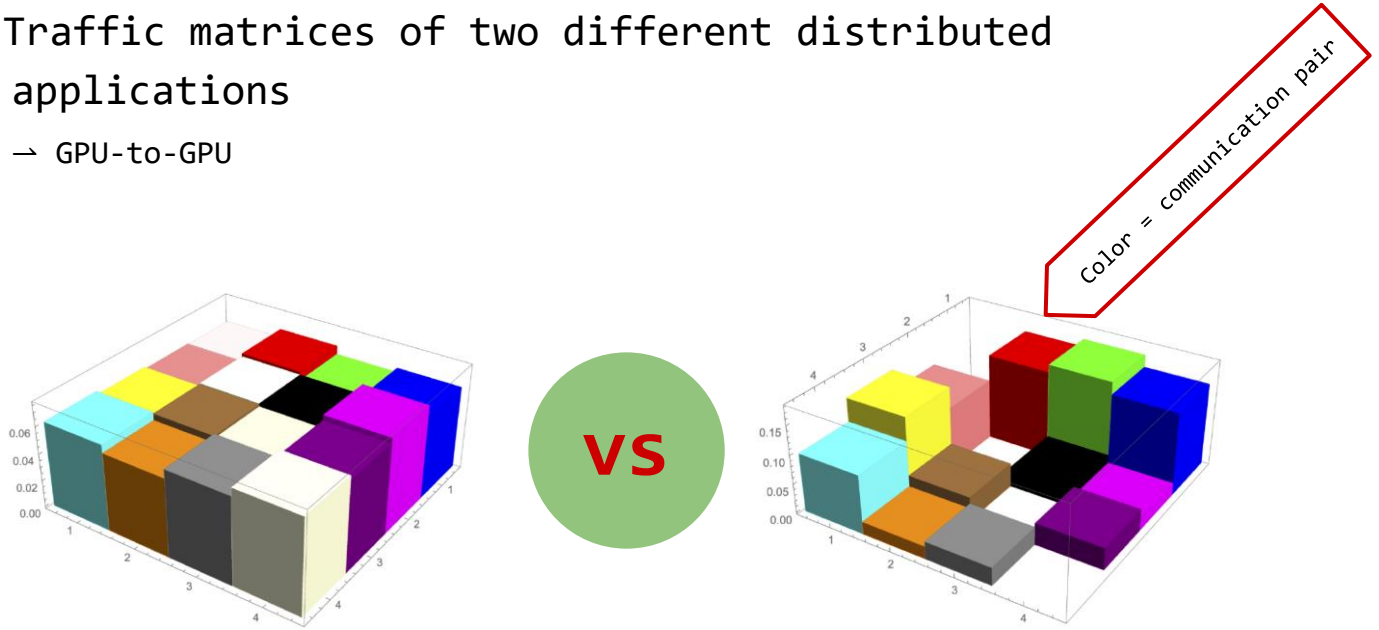


Intuition

Which demand has more structure?

⇢ Traffic matrices of two different distributed ML applications

→ GPU-to-GPU



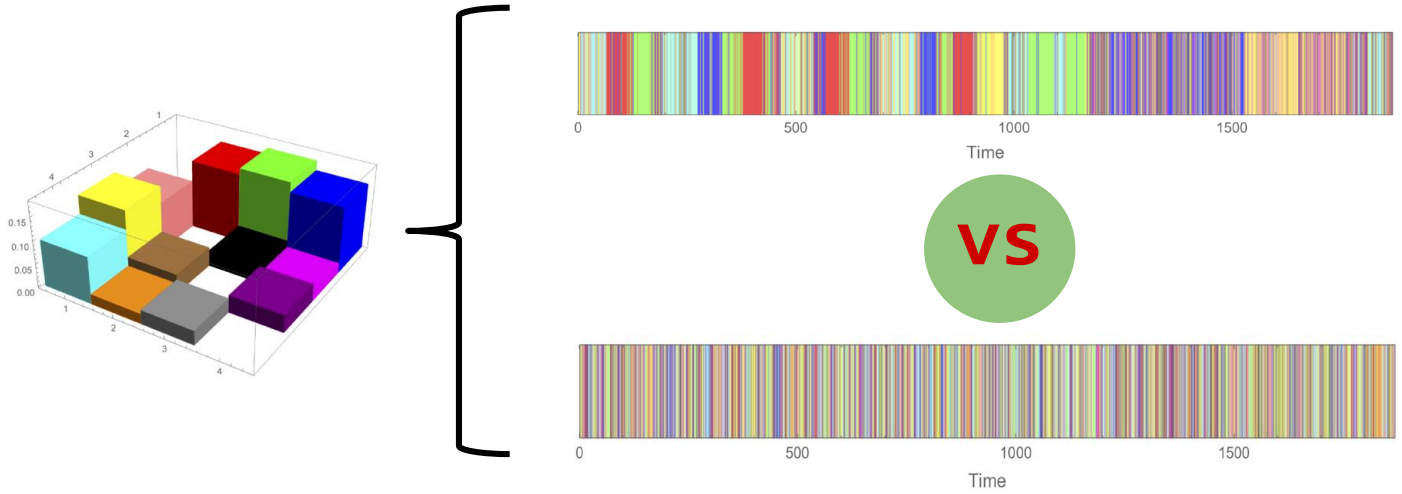
More uniform **More structure**

Intuition

Spatial vs temporal structure

⇢ Two different ways to generate same traffic matrix:
  ⇀ Same non-temporal structure

⇢ Which one has more structure?



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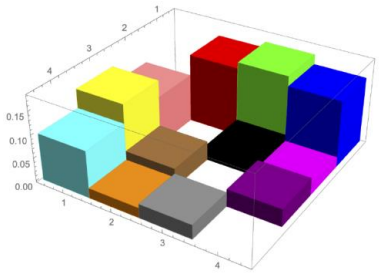
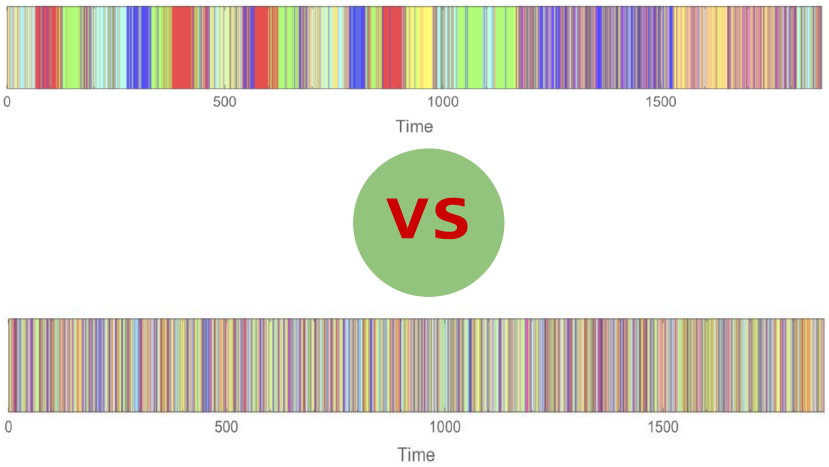


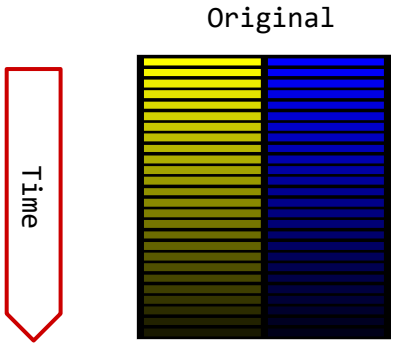


Systematically?

Trace Complexity

Information-Theoretic Approach

“Shuffle&Compress”



Trace Complexity

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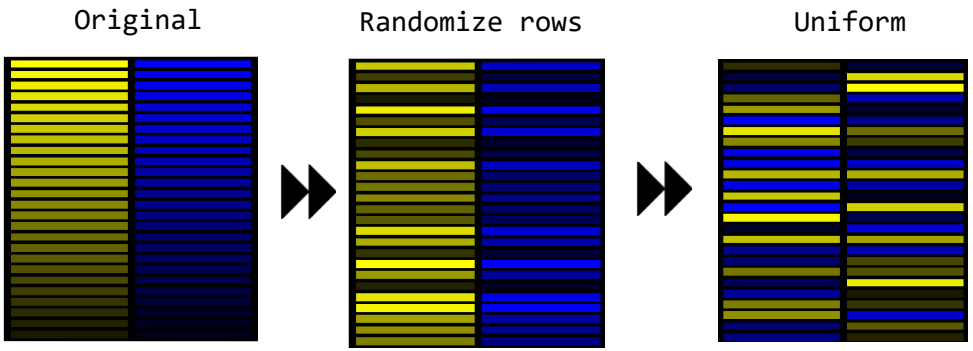

Increasing complexity (systematically randomized)

More structure (compresses better)

Trace Complexity

Information-Theoretic Approach

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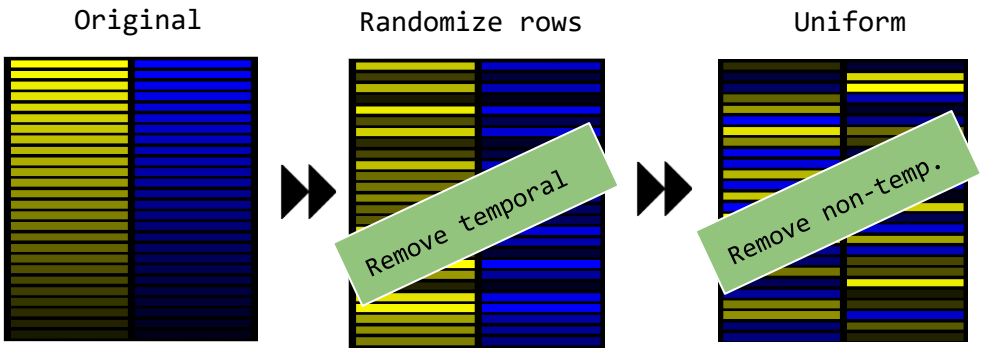

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Information-Theoretic Approach

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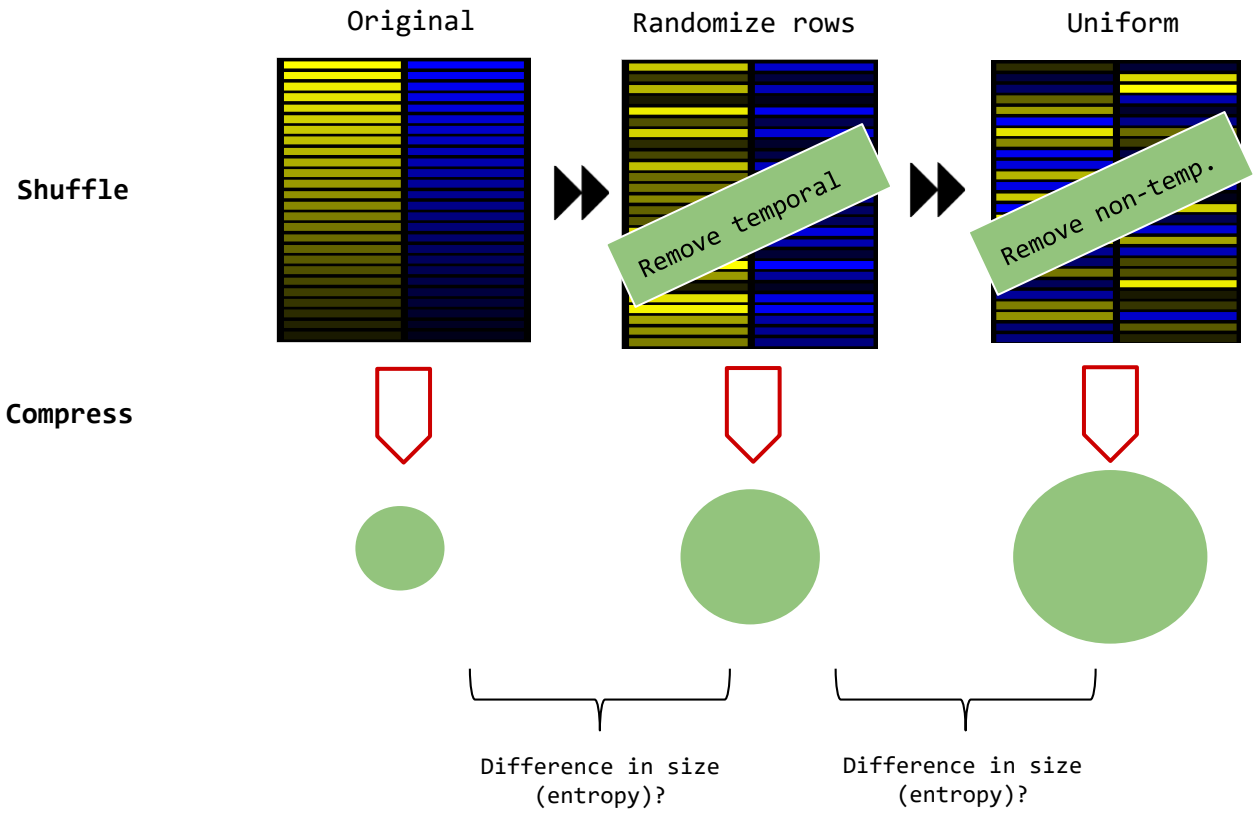
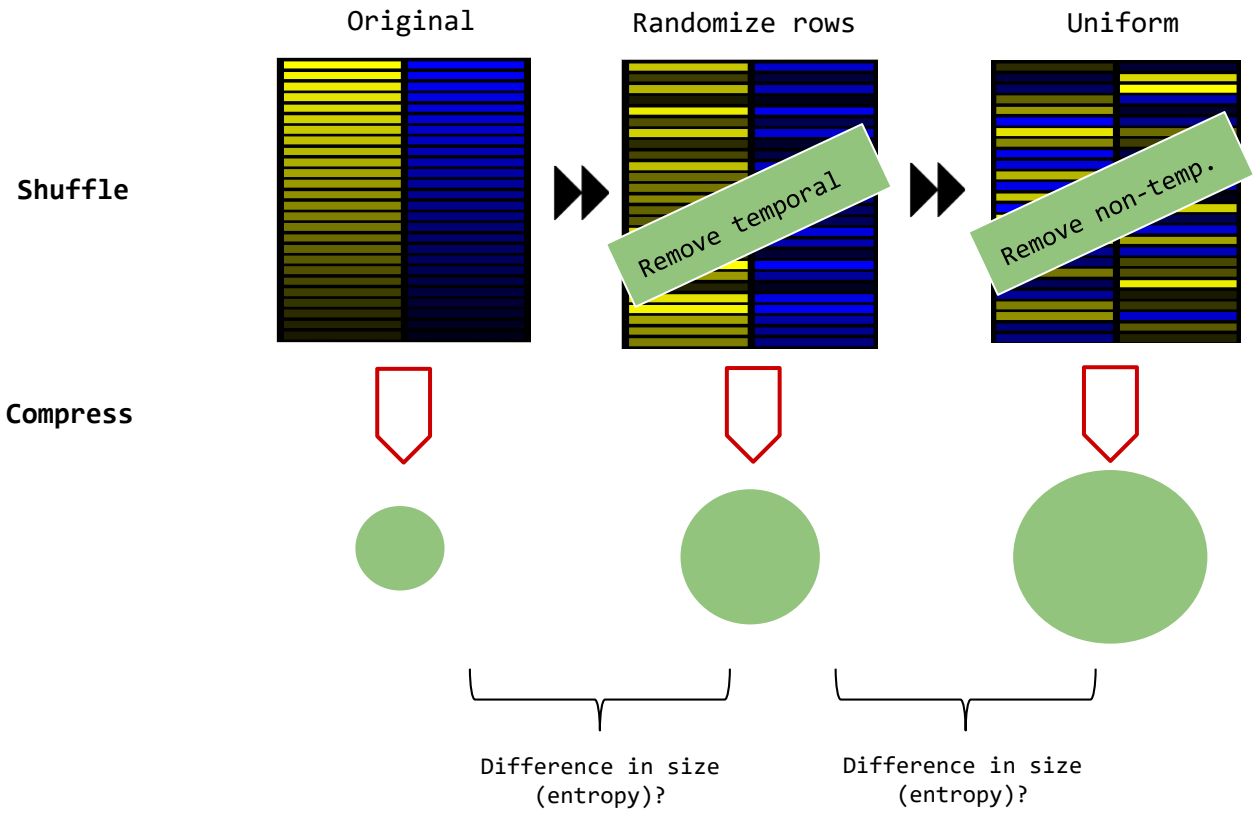


Trace Complexity

Information-Theoretic Approach

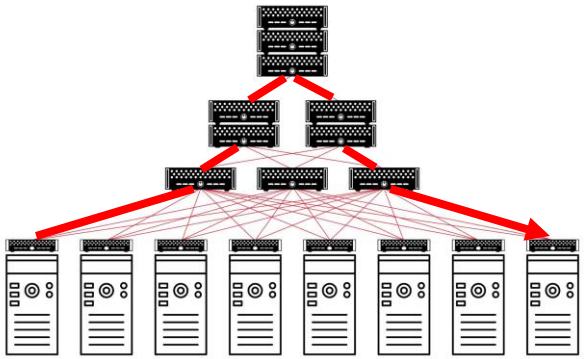
“Shuffle&Compress”



Can be used to define 2-dimensional complexity map!

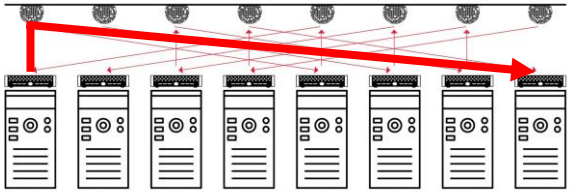
It is more complicated…

→ Self-adjusting networks may be really useful to serve large flows (elephant flows): avoiding multi-hop routing



6 hops

vs



1 hop

It is more complicated…

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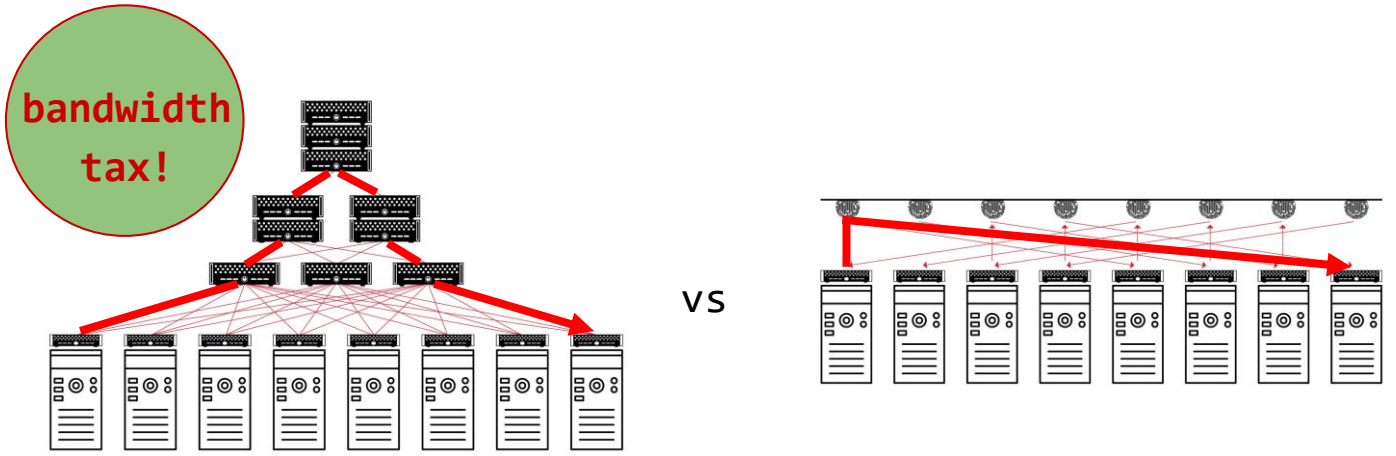

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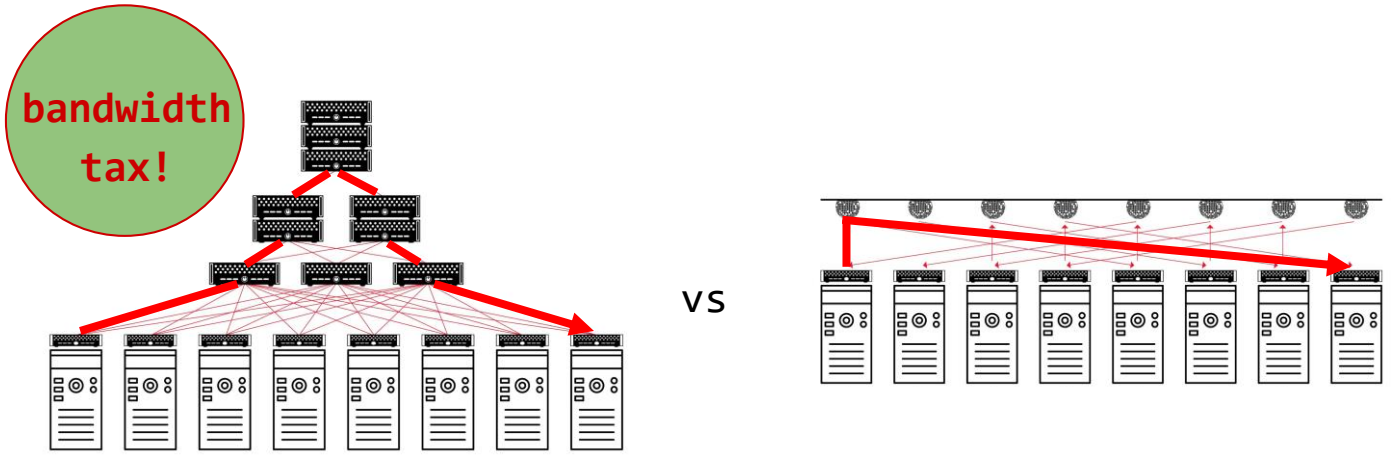

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→ However, requires optimization and adaption, which takes time

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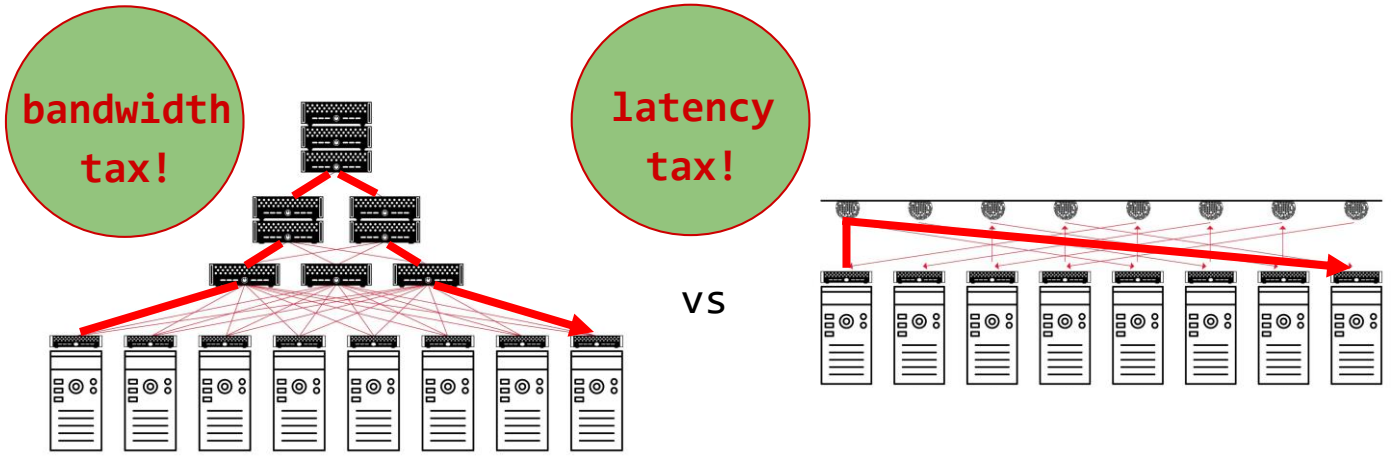


→ However, requires optimization and adaption, which takes time

Indeed, it is more complicated than that…

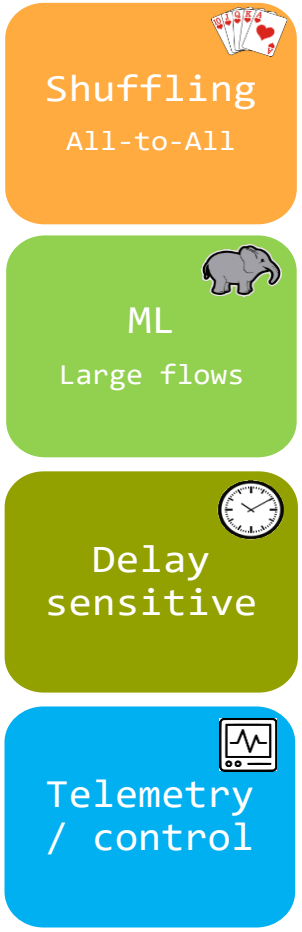
Challenge: Traffic Diversity

Diverse patterns:

- Shuffling/Hadoop: all-to-all
- All-reduce/ML: ring or tree traffic patterns
  - Elephant flows
- Query traffic: skewed
  - Mice flows
- Control traffic: does not evolve but has non-temporal structure

Diverse requirements:

- ML is bandwidth hungry, small flows are latency-sensitive



Opportunity: Tech Diversity

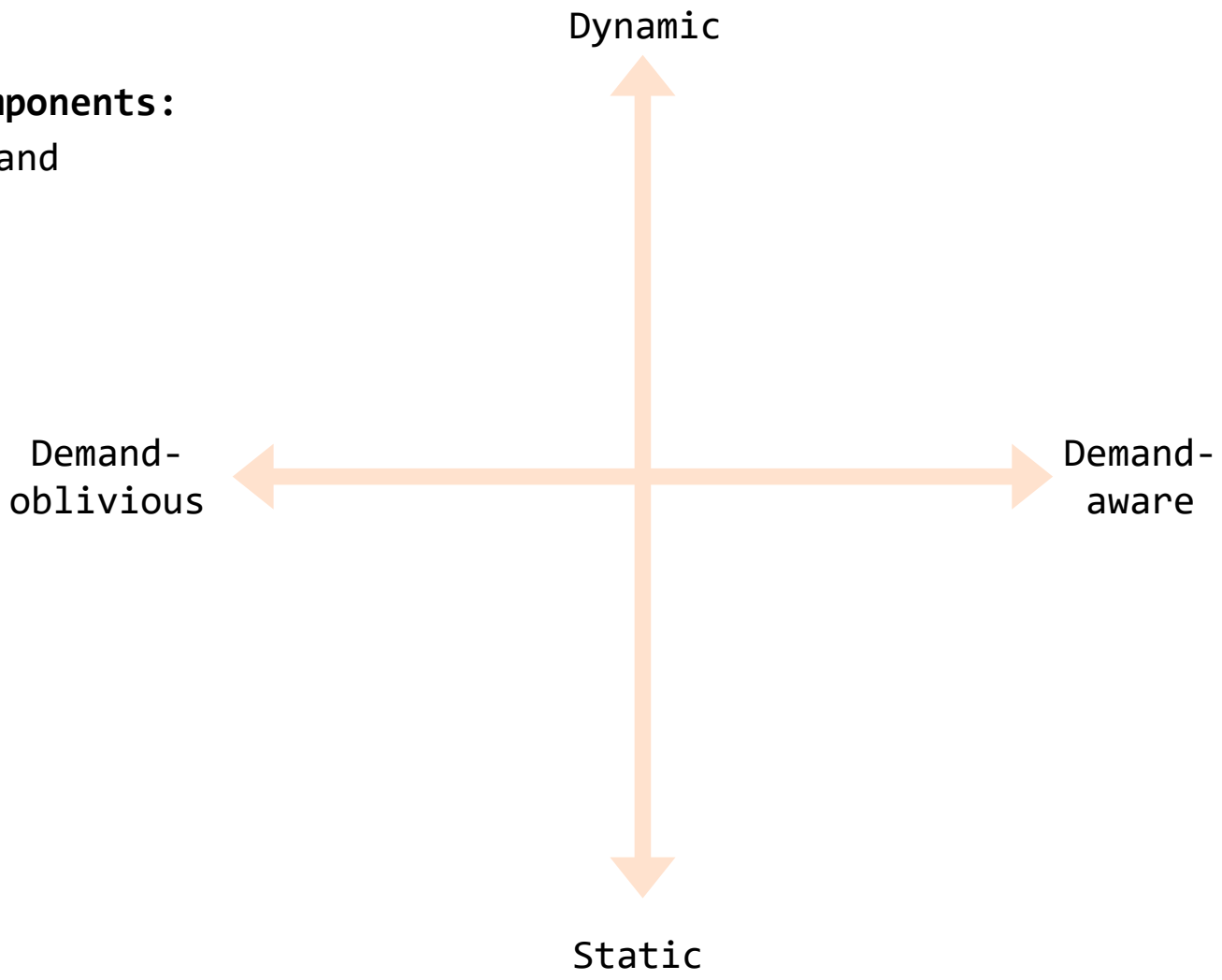
Diverse topology components:

→ demand-oblivious and
demand-aware

Opportunity: Tech Diversity

Diverse topology components:

- demand-oblivious and demand-aware
- static vs dynamic



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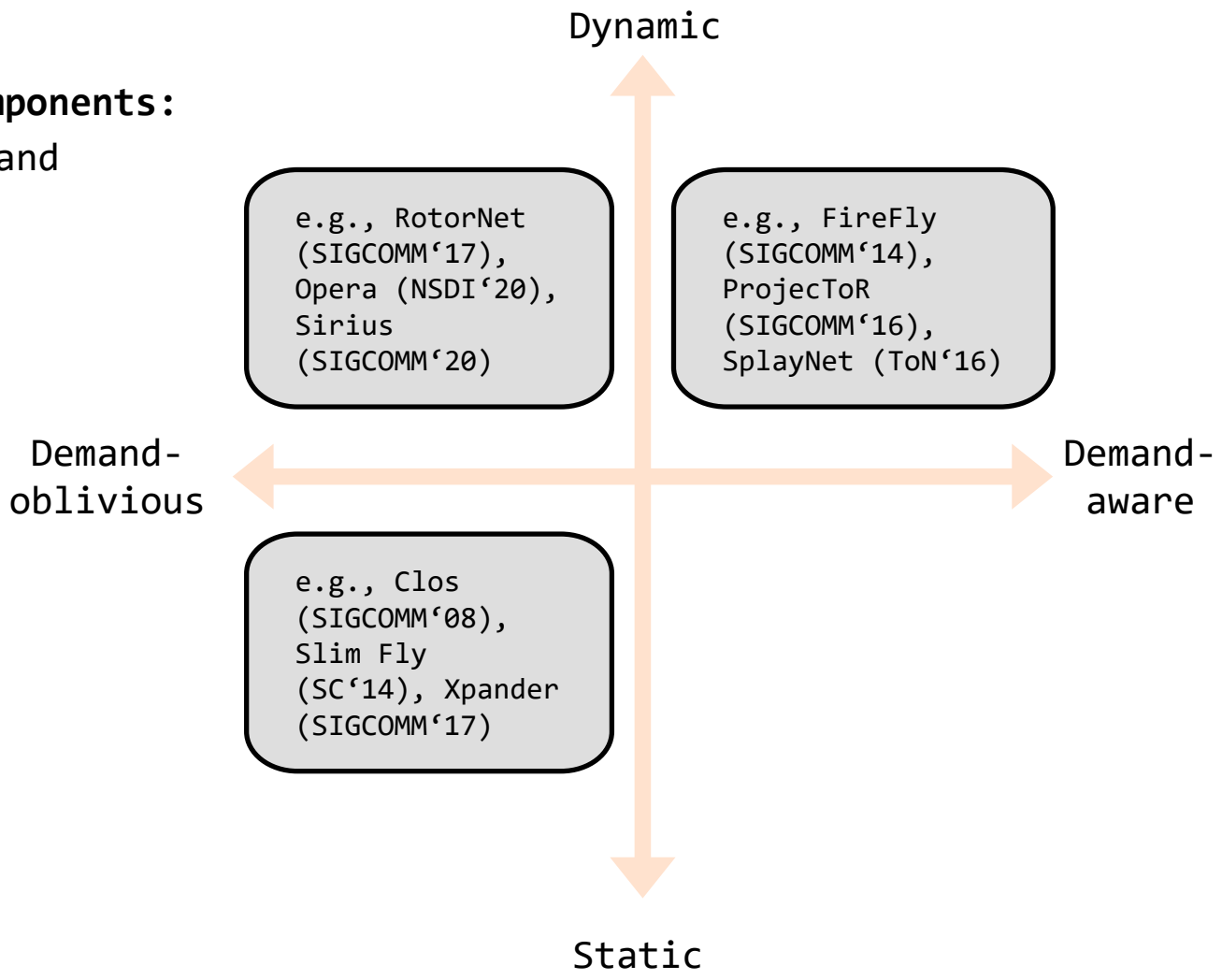

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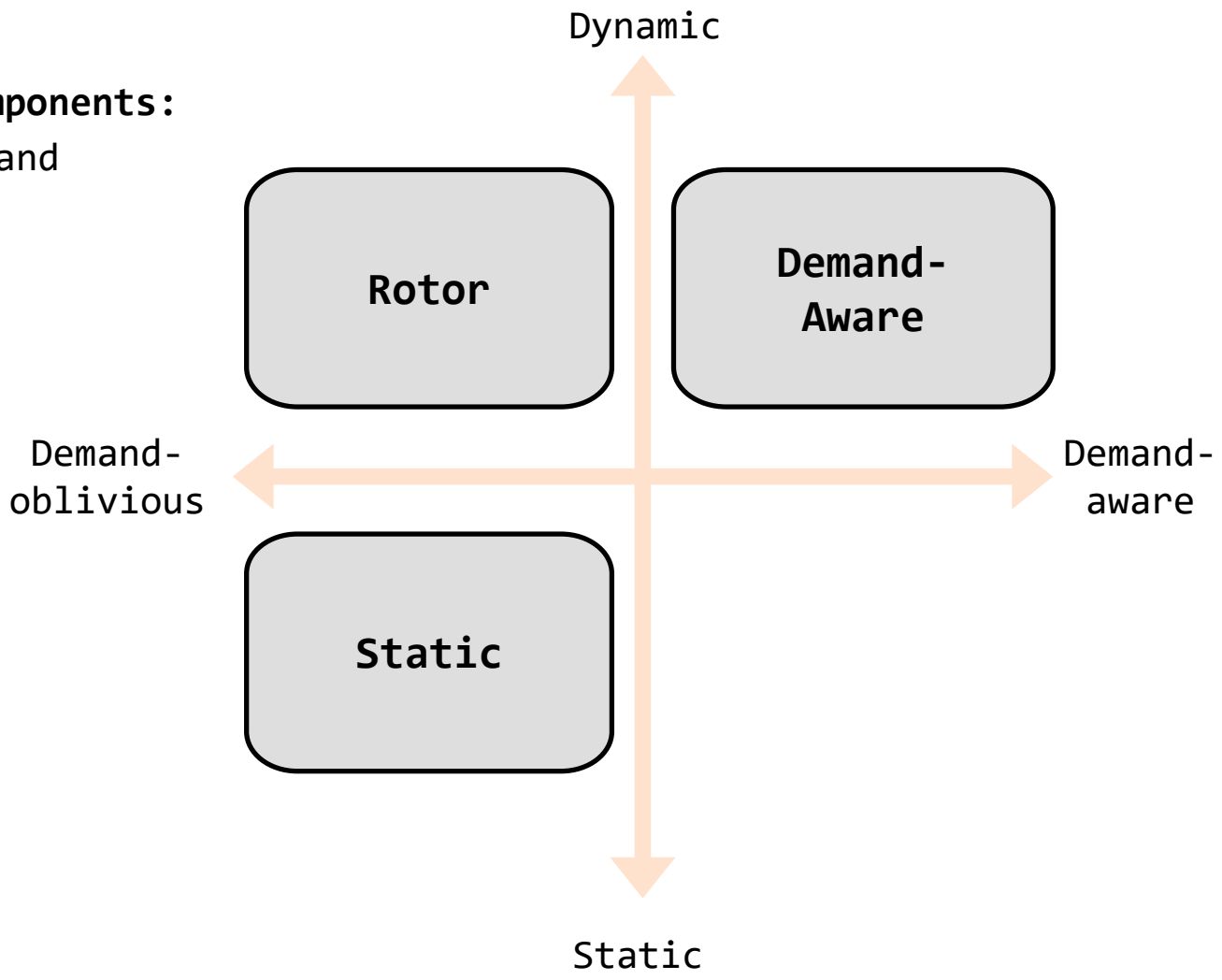

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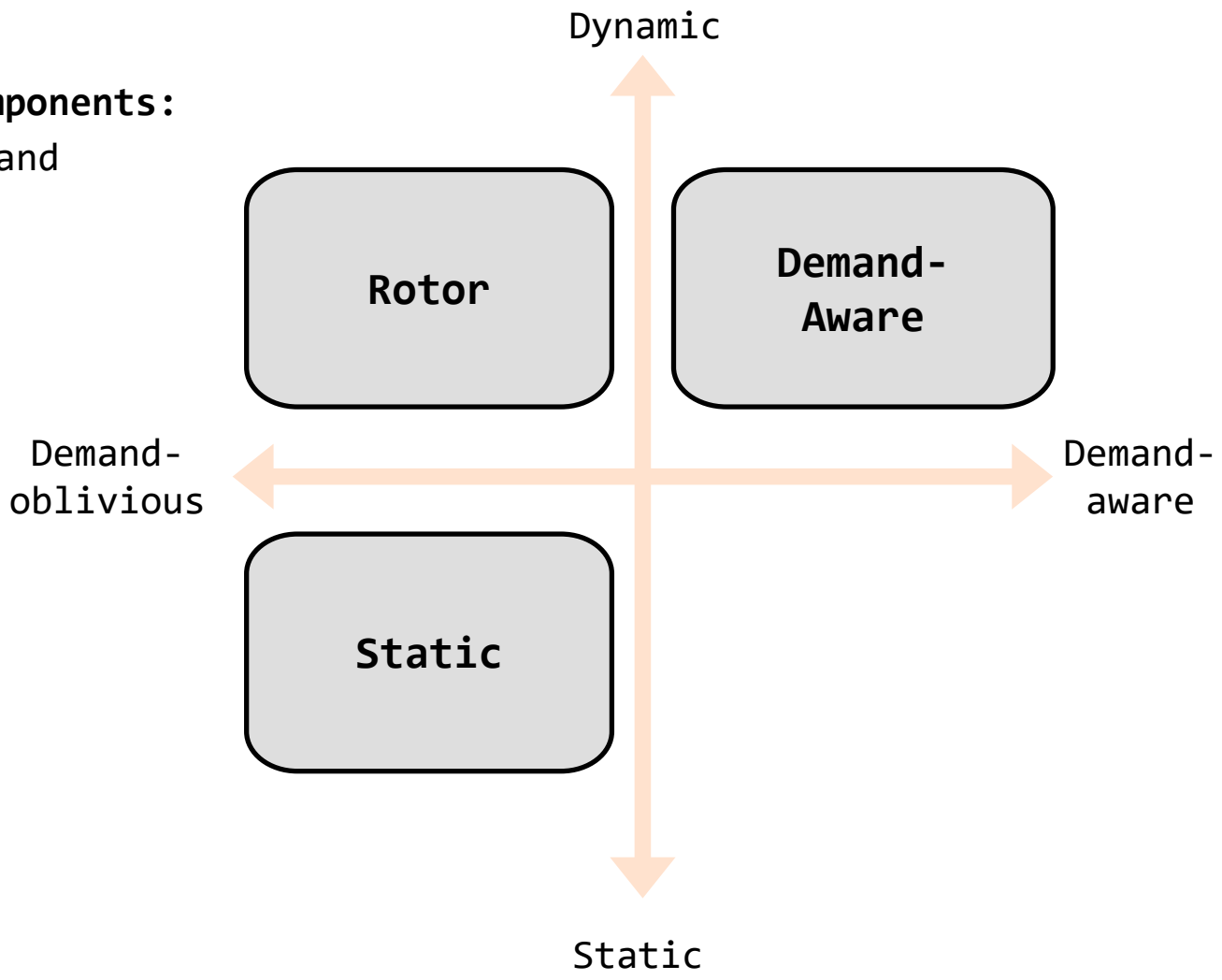

Which approach is best?

Opportunity: Tech Diversity

Diverse topology components:

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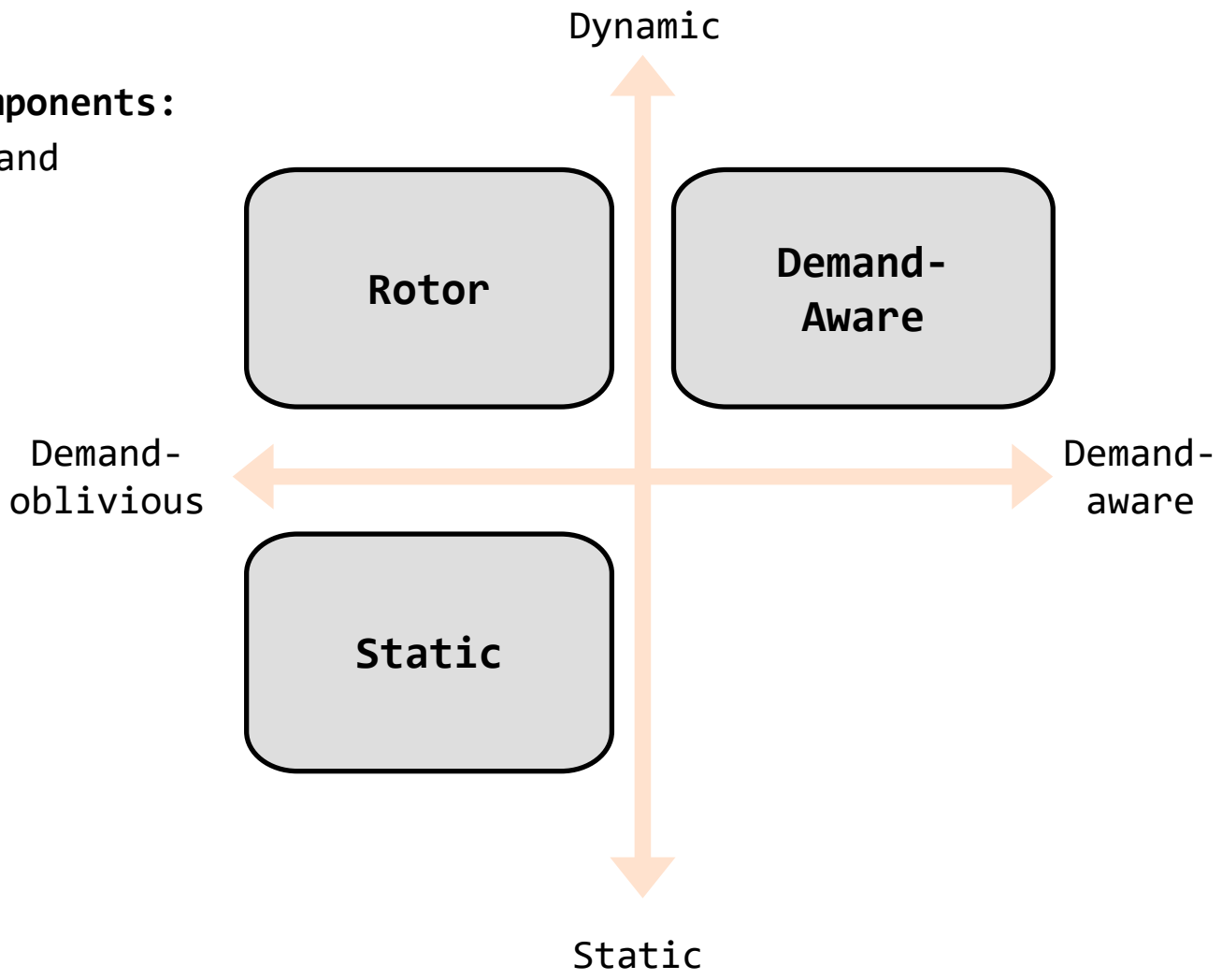
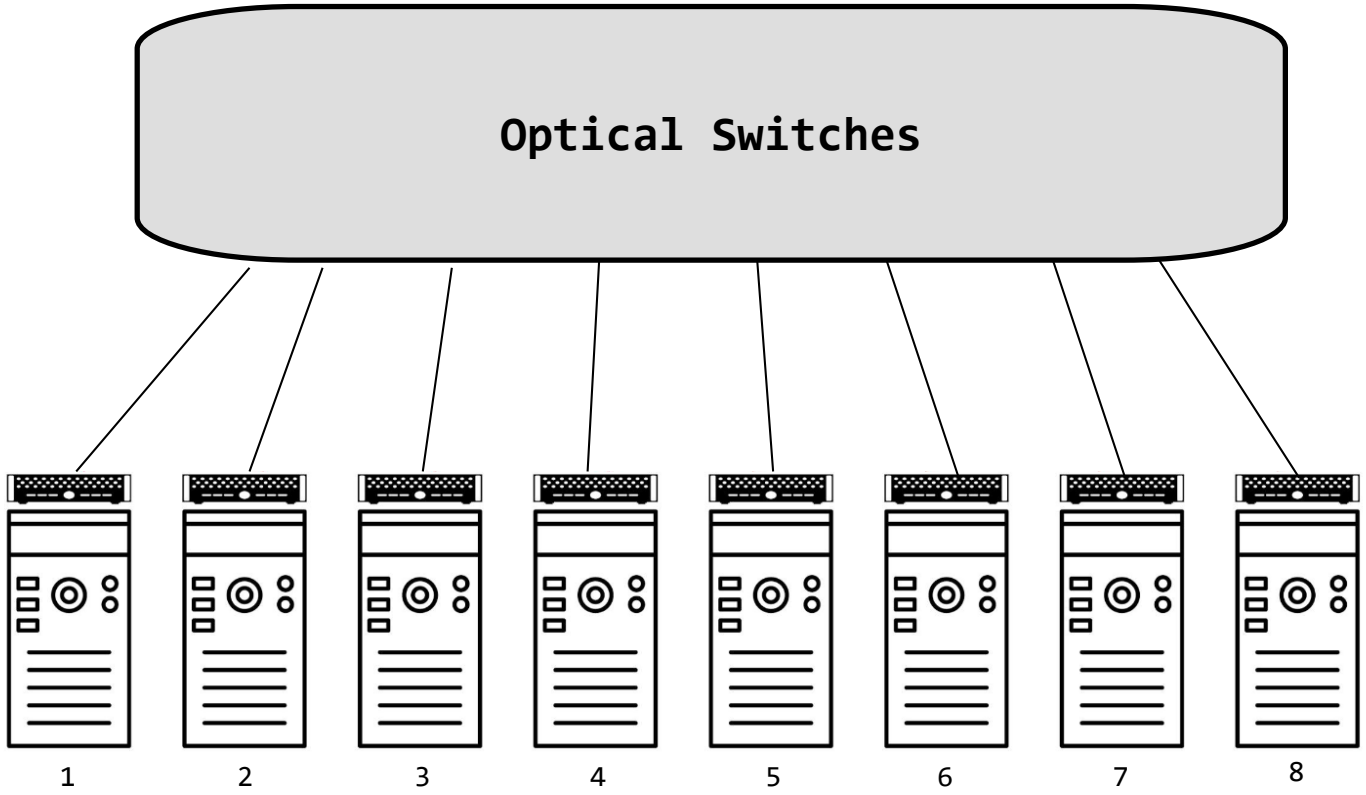


Which approach is best?

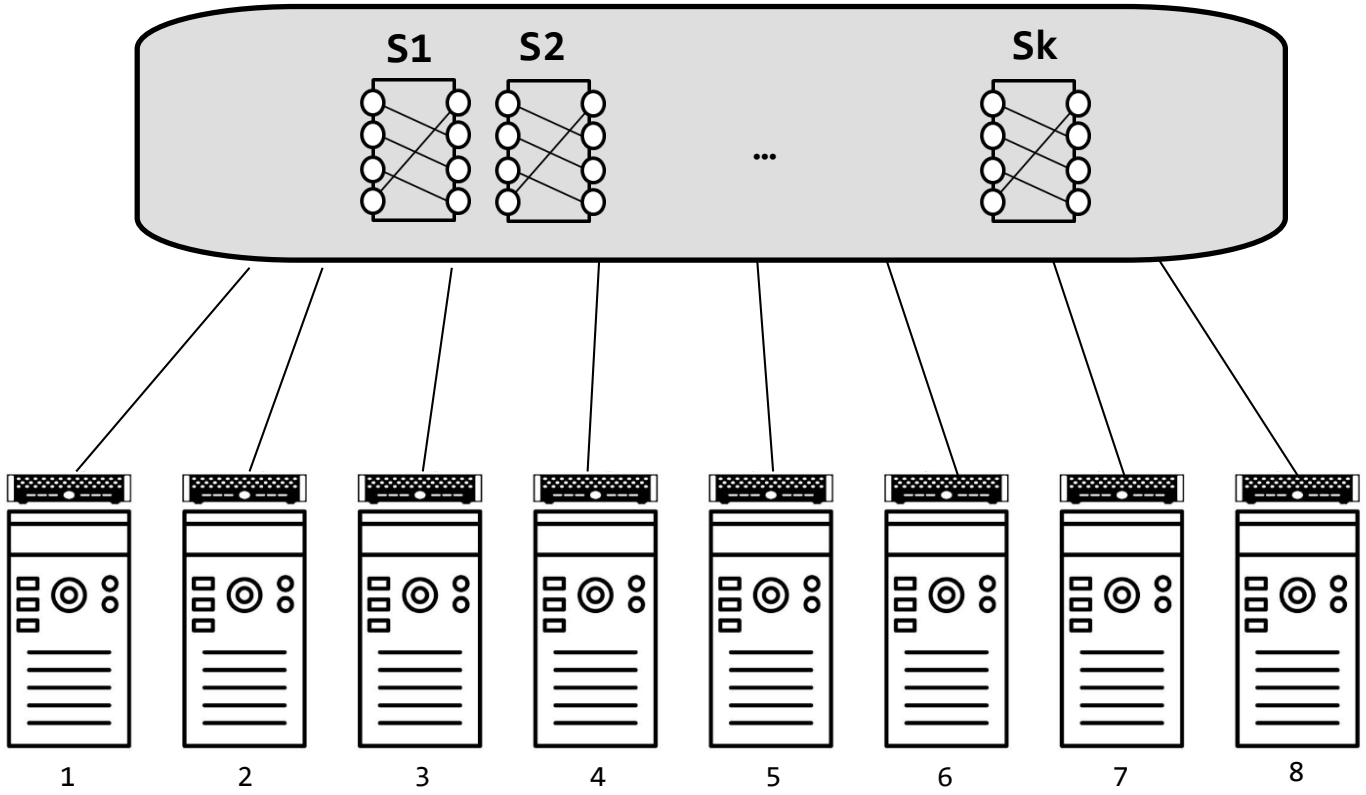
As always in CS: It depends…

Rack Interconnect



Typical rack internconnect: ToR-Matching-ToR (TMT) model

Rack Interconnect

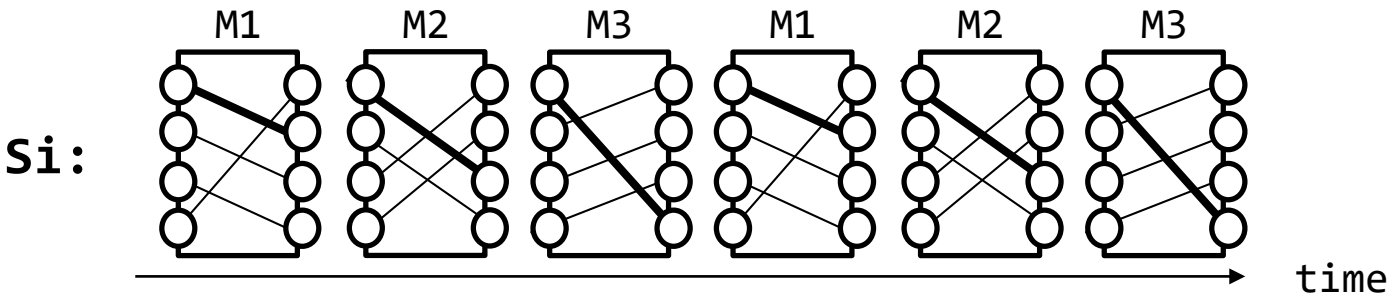


Typical rack internconnect: ToR-Matching-ToR (TMT) model

Details: Switch Types

Periodic Switch (aka Rotor Switch)

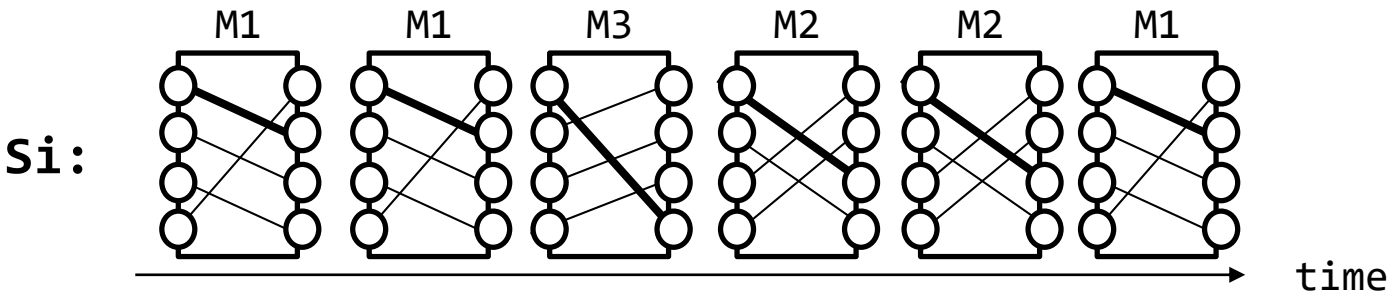
Rotor switch: periodic matchings (demand-oblivious)



Details: Switch Types

Demand-Aware Switch

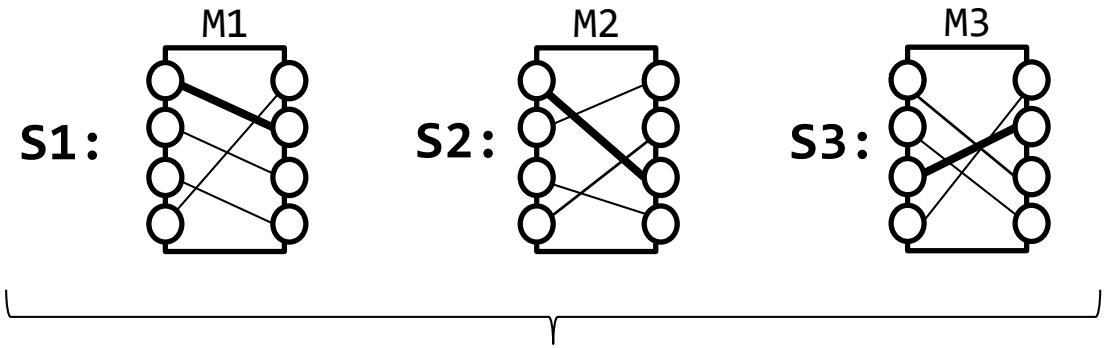
Demand-aware switch: optimized matchings

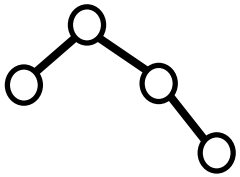


Details: Switch Types

Static Switch

Static switches: combine for optimized static topology

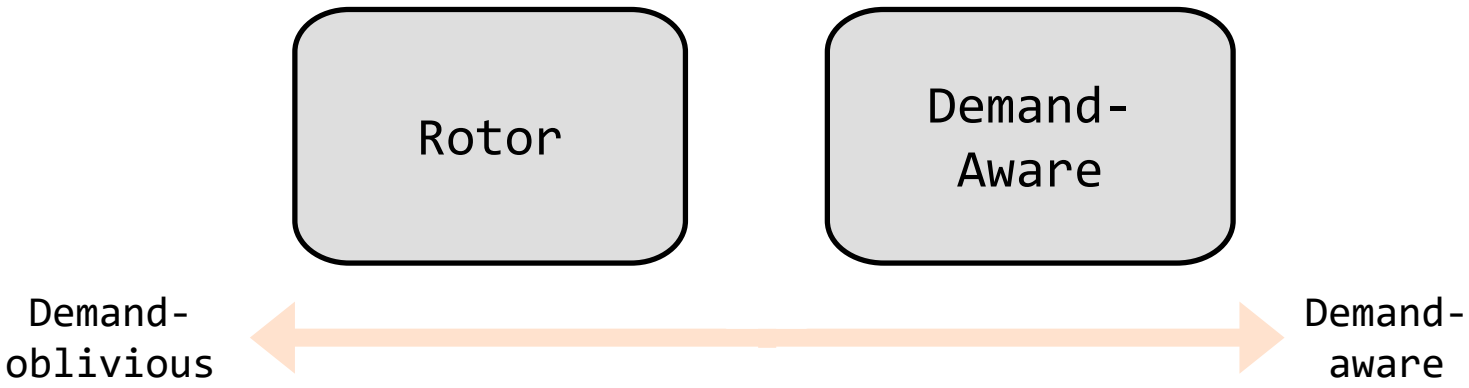




e.g, tree, expander

Design Tradeoffs (1)

The “Awareness-Dimension”



Good for all-to-all traffic!

→ oblivious: very fast
periodic direct connectivity

→ no control plane overhead

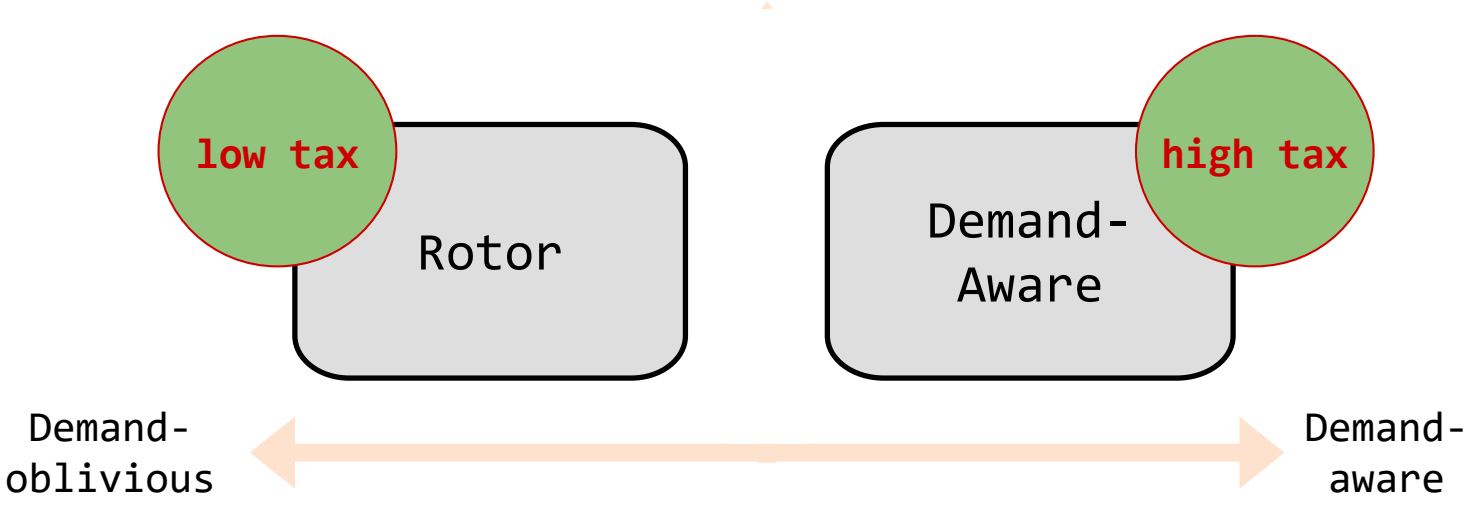
Good for elephant flows!

→ optimizable toward traffic

→ but slower

Design Tradeoffs (1)

The “Awareness-Dimension”



Good for all-to-all traffic!

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periodic direct connectivity

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Good for elephant flows!

→ optimizable toward traffic

→ but slower

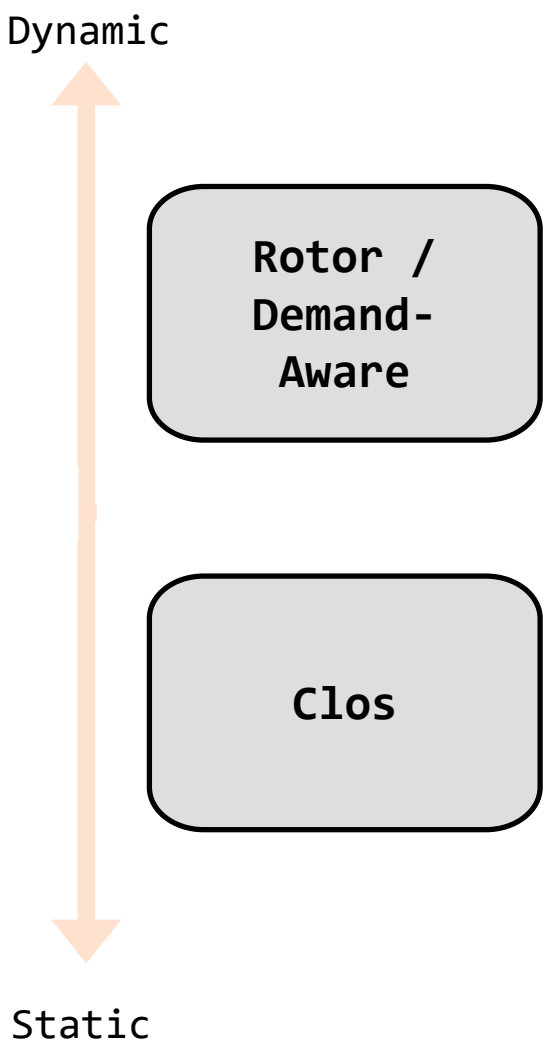
Compared to static networks: latency tax!

Design Tradeoffs (2)

The “Flexibility-Dimension”

Good for high throughput!
→ direct connectivity saves bandwidth along links

Good for low latency!
→ no need to wait for reconfigurable links
→ **compared to dynamic: bandwidth tax (multi-hop)**



Design Tradeoffs (2)

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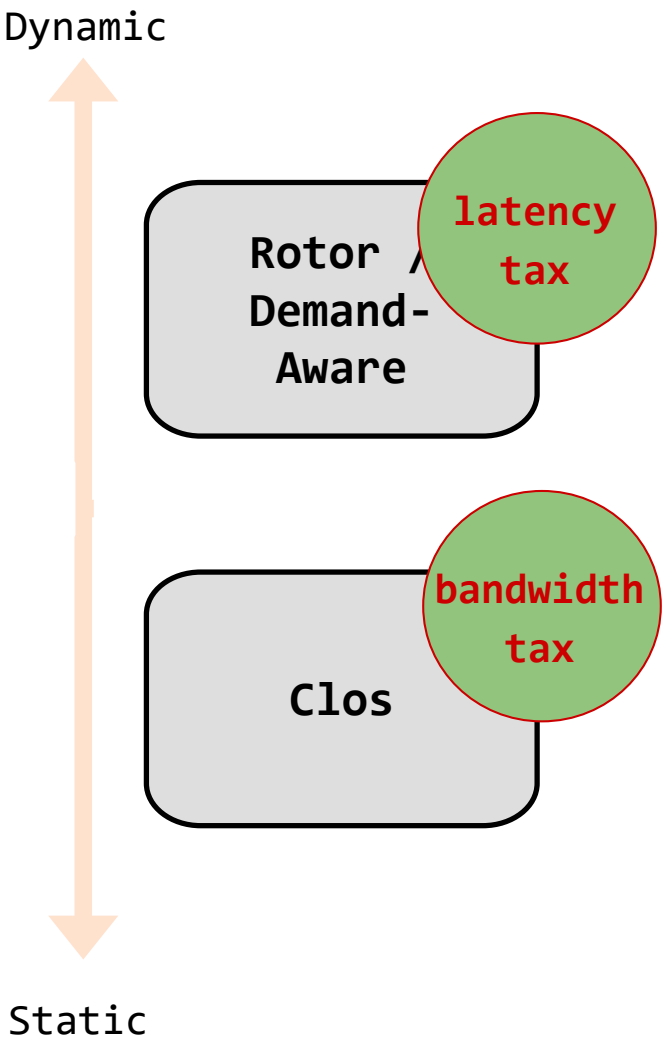


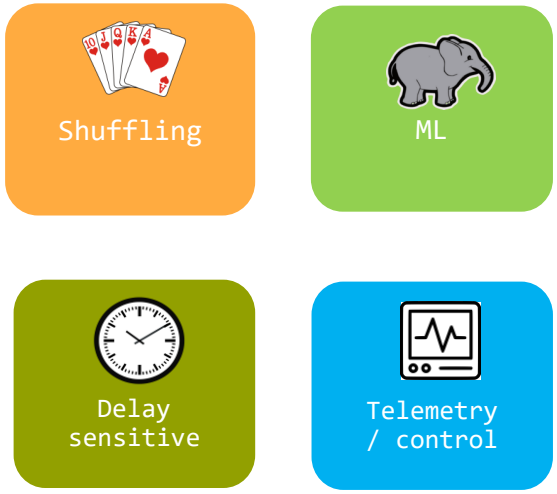
First Observations

⇢ **Observation 1:** Different topologies provide different tradeoffs.

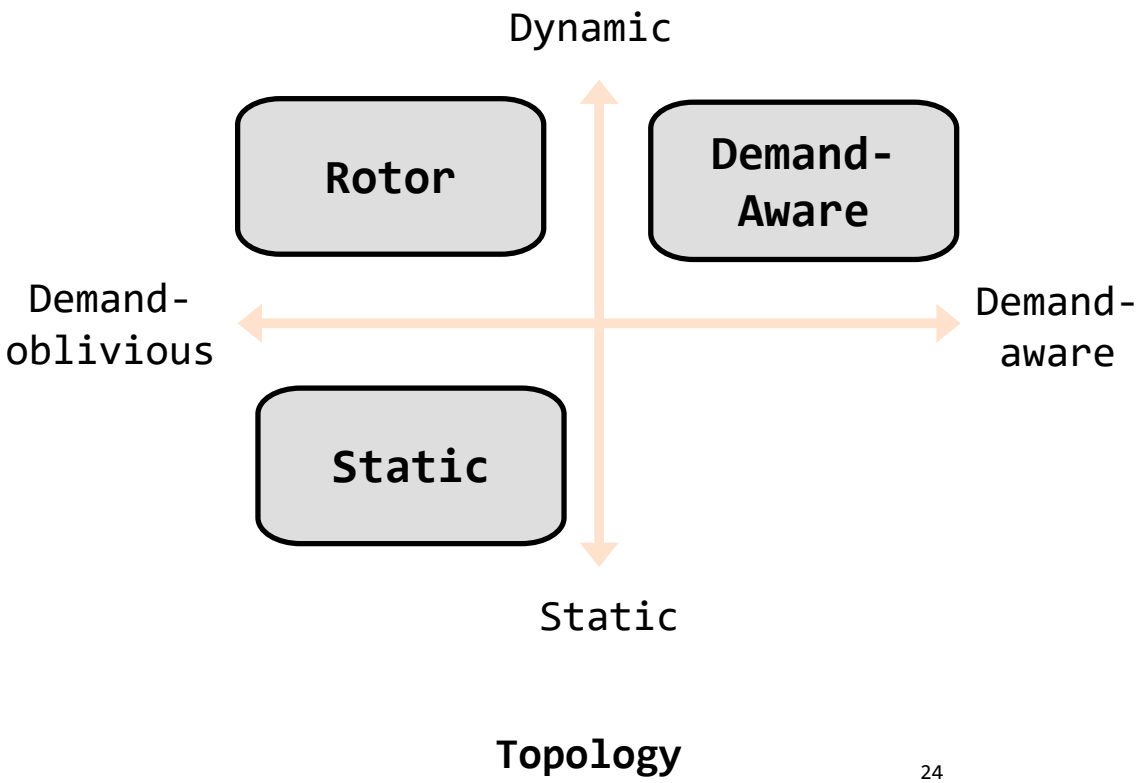
⇢ **Observation 2:** Different traffic requires different topology types.

⇢ **Observation 3:** A **mismatch of demand** and topology can increase **flow completion times**.

Examples:
Match or Mismatch?



Demand



Topology

Examples:
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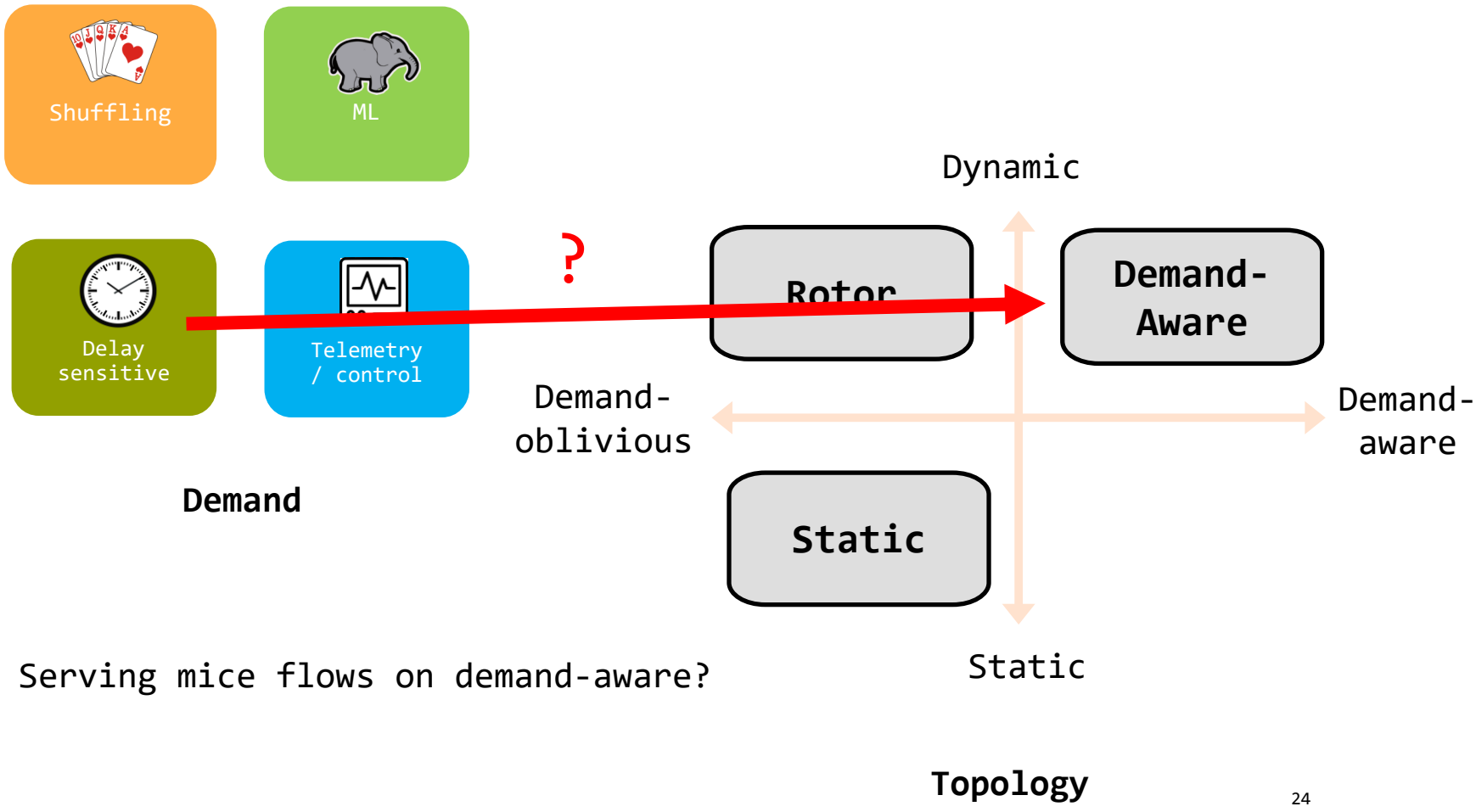
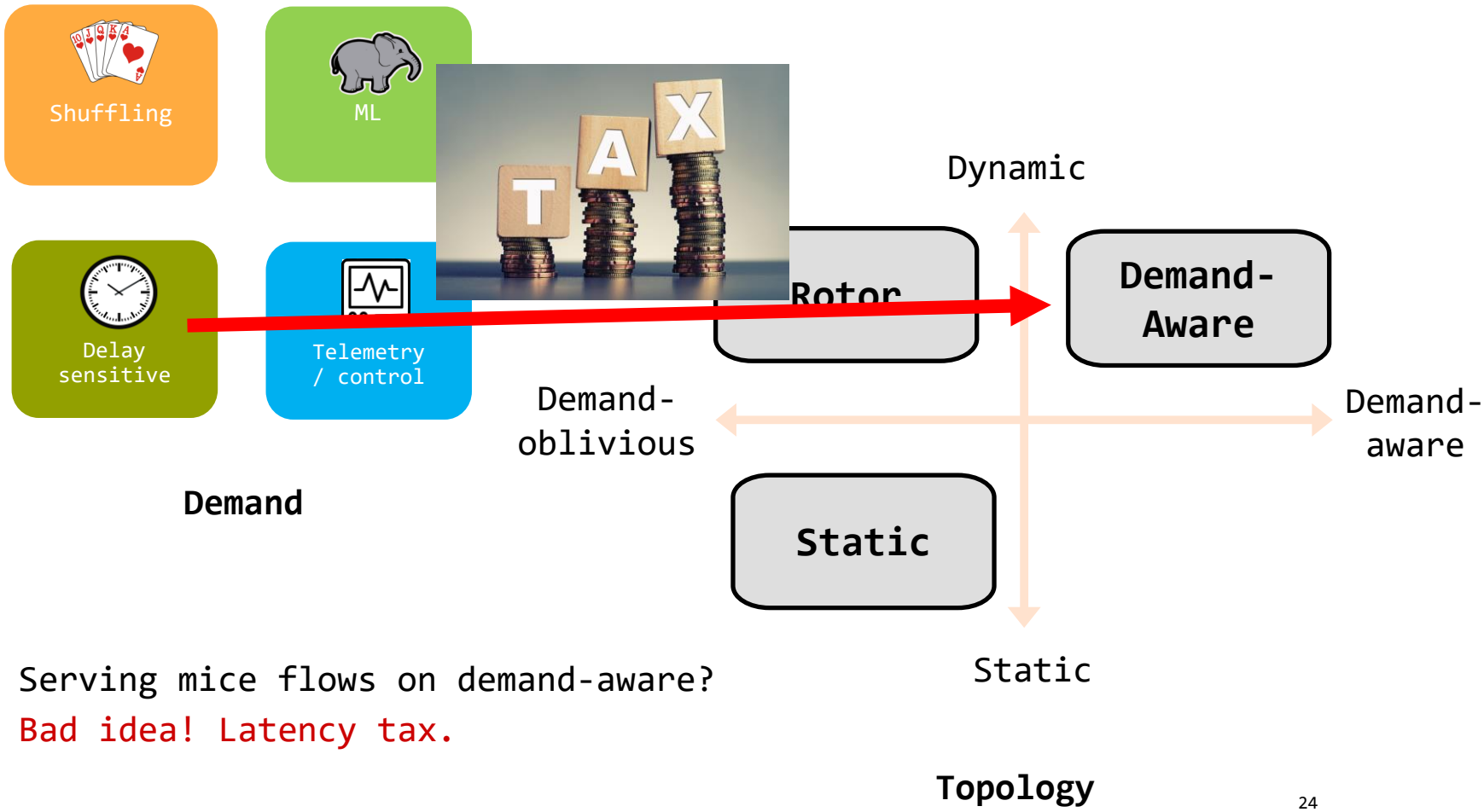


Serving mice flows on demand-aware?

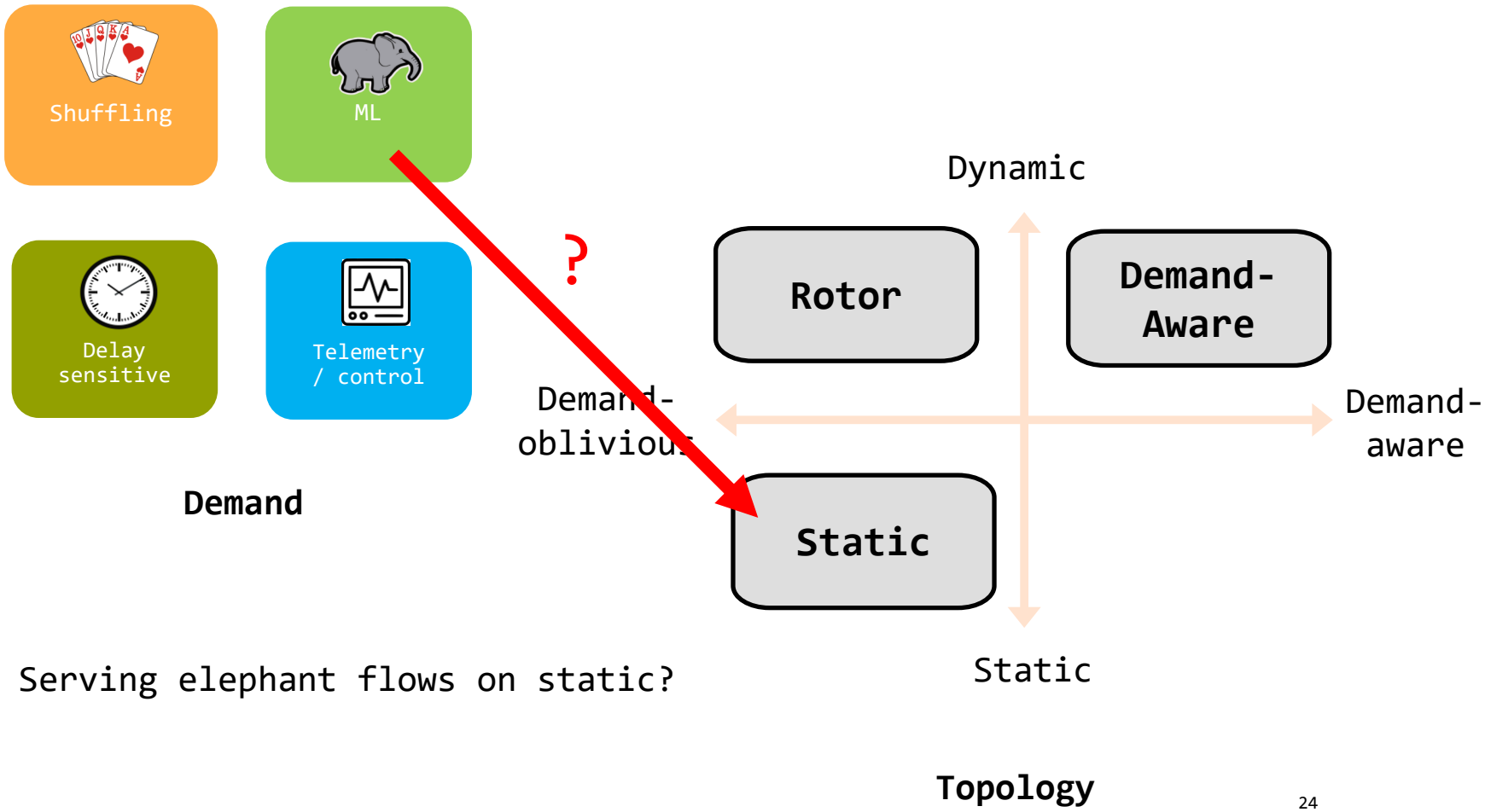
Examples:
Match or Mismatch?



Serving mice flows on demand-aware?

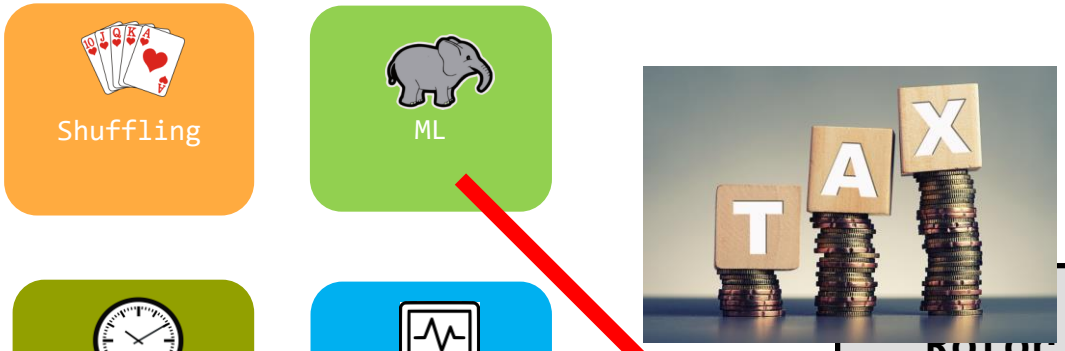
Bad idea! Latency tax.

Examples:
Match or Mismatch?



Serving elephant flows on static?

Examples:
Match or Mismatch?

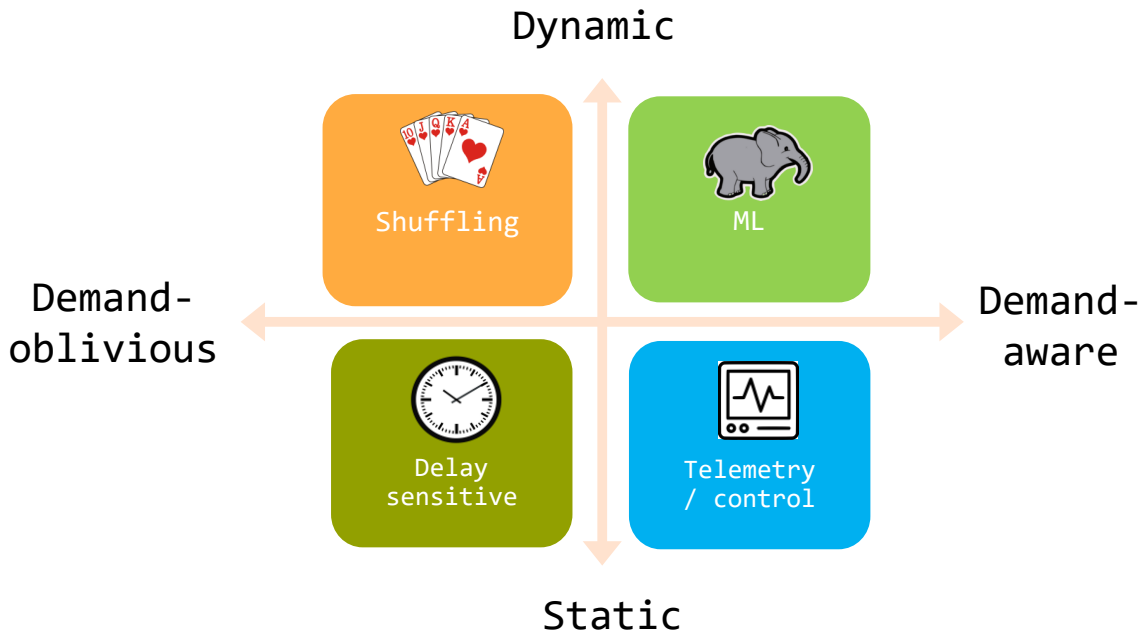


Demand

Serving elephant flows on static?

Bad idea! Bandwidth tax.

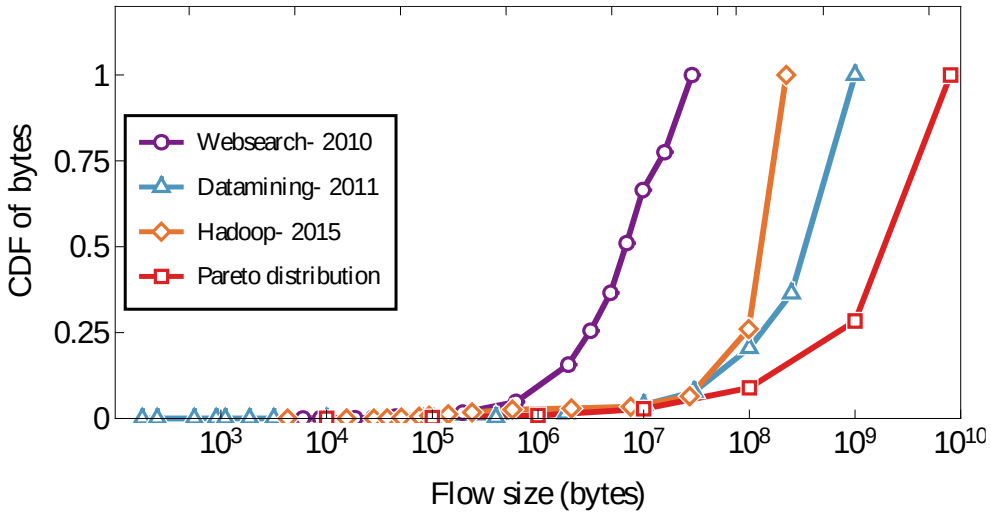
Cerberus: It's a Match!



Our system Cerberus* serves traffic on the "best topology"!

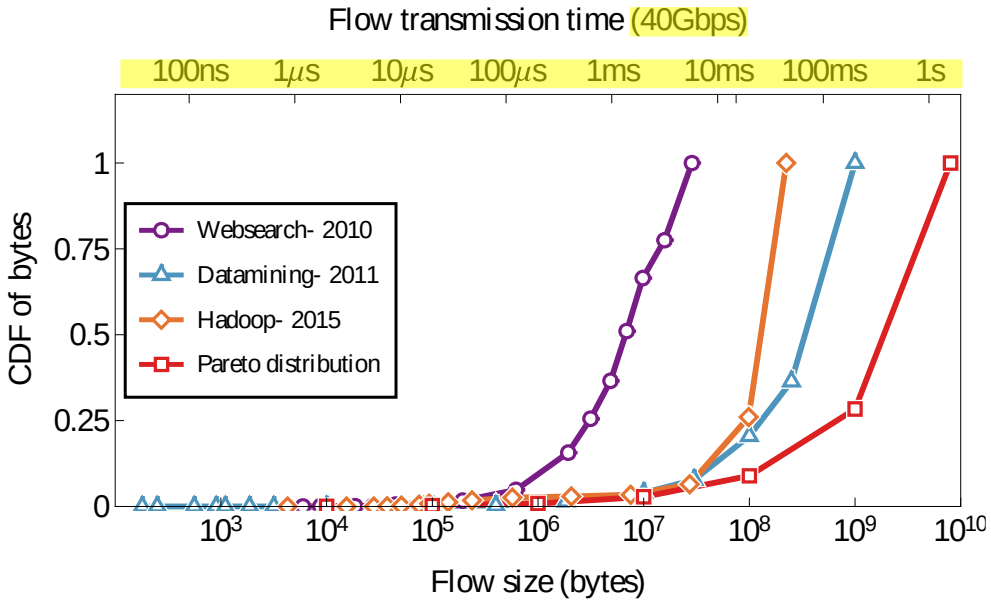
* Griner et al., ACM SIGMETRICS 2022

Flow Size Matters



⇢ **Observation 1:** Different apps have different flow size distributions.

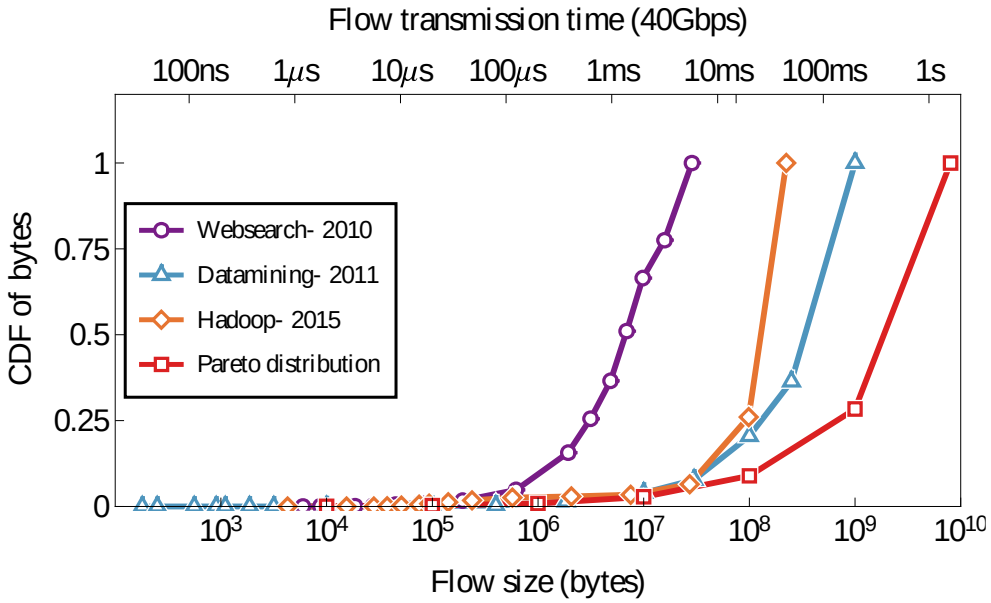
Flow Size Matters



⇢ **Observation 1:** Different apps have different flow size distributions.

⇢ **Observation 2:** The transmission time of a flow depends on its size.

Flow Size Matters



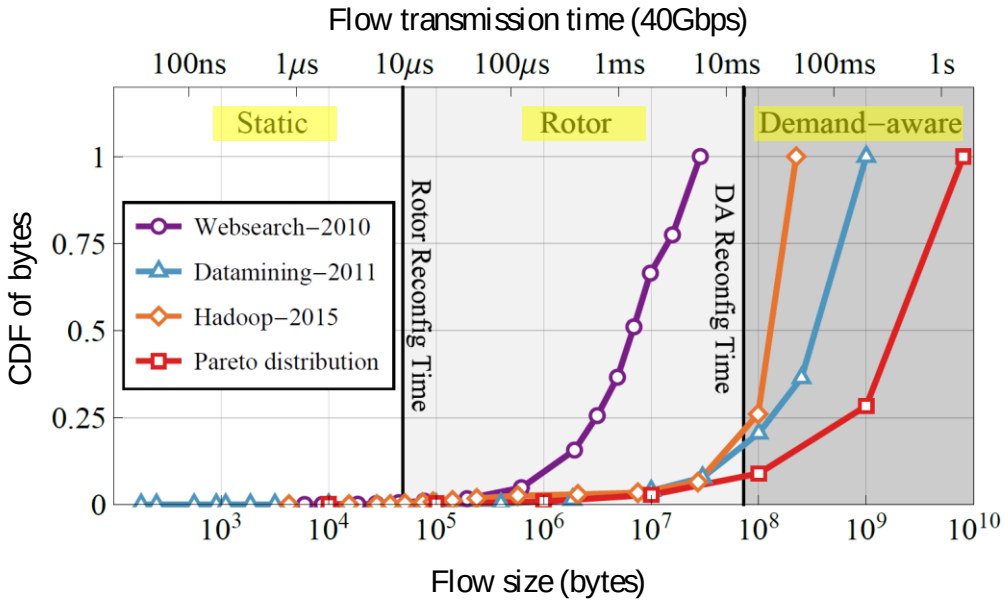
⇢ **Observation 1:** Different apps have different flow size distributions.

⇢ **Observation 2:** The transmission time of a flow depends on its size.

⇢ **Observation 3:** For small flows, flow completion time suffers if network needs to be reconfigured first.

⇢ **Observation 4:** For large flows, reconfiguration time may amortize.

Flow Size Matters



It's a Match!

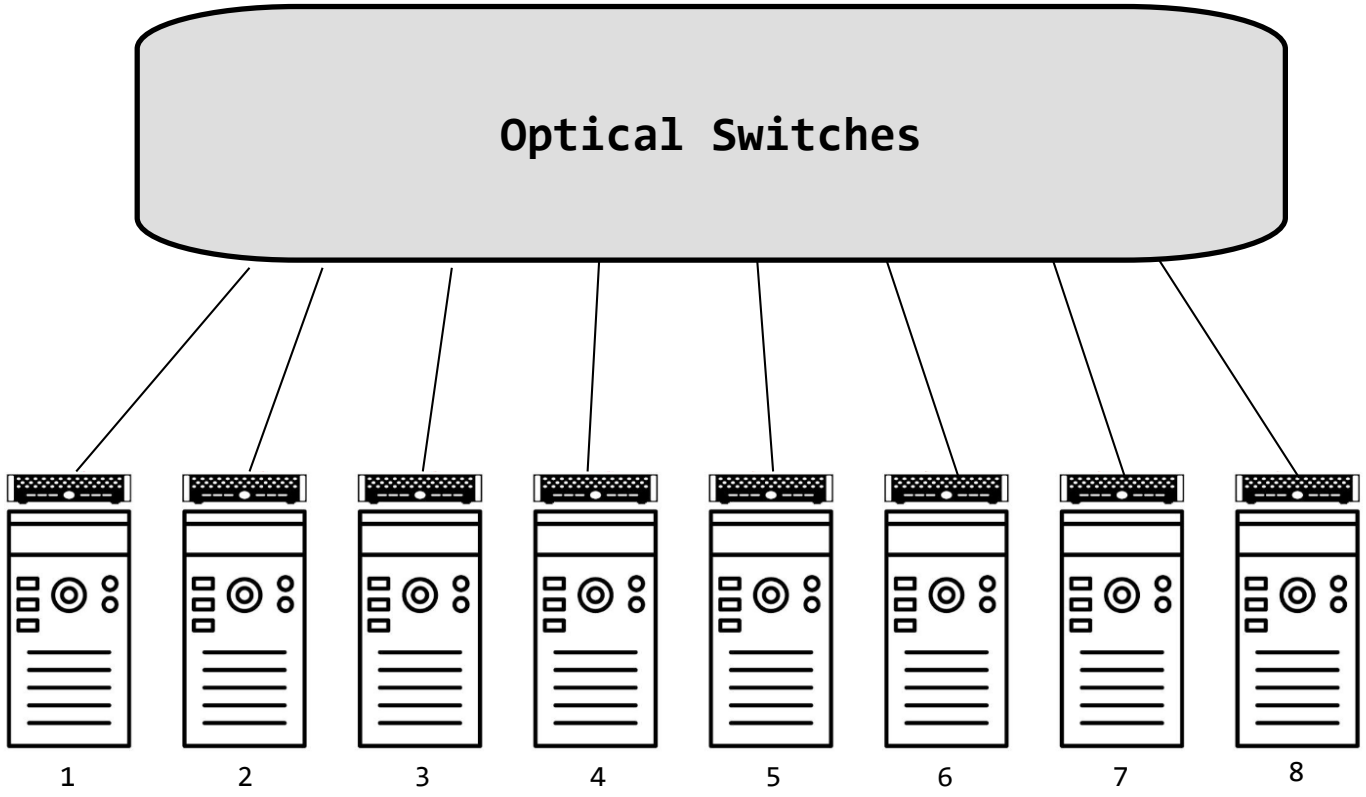
⇢ **Observation 1:** Different apps have different flow size distributions.

⇢ **Observation 2:** The transmission time of a flow depends on its size.

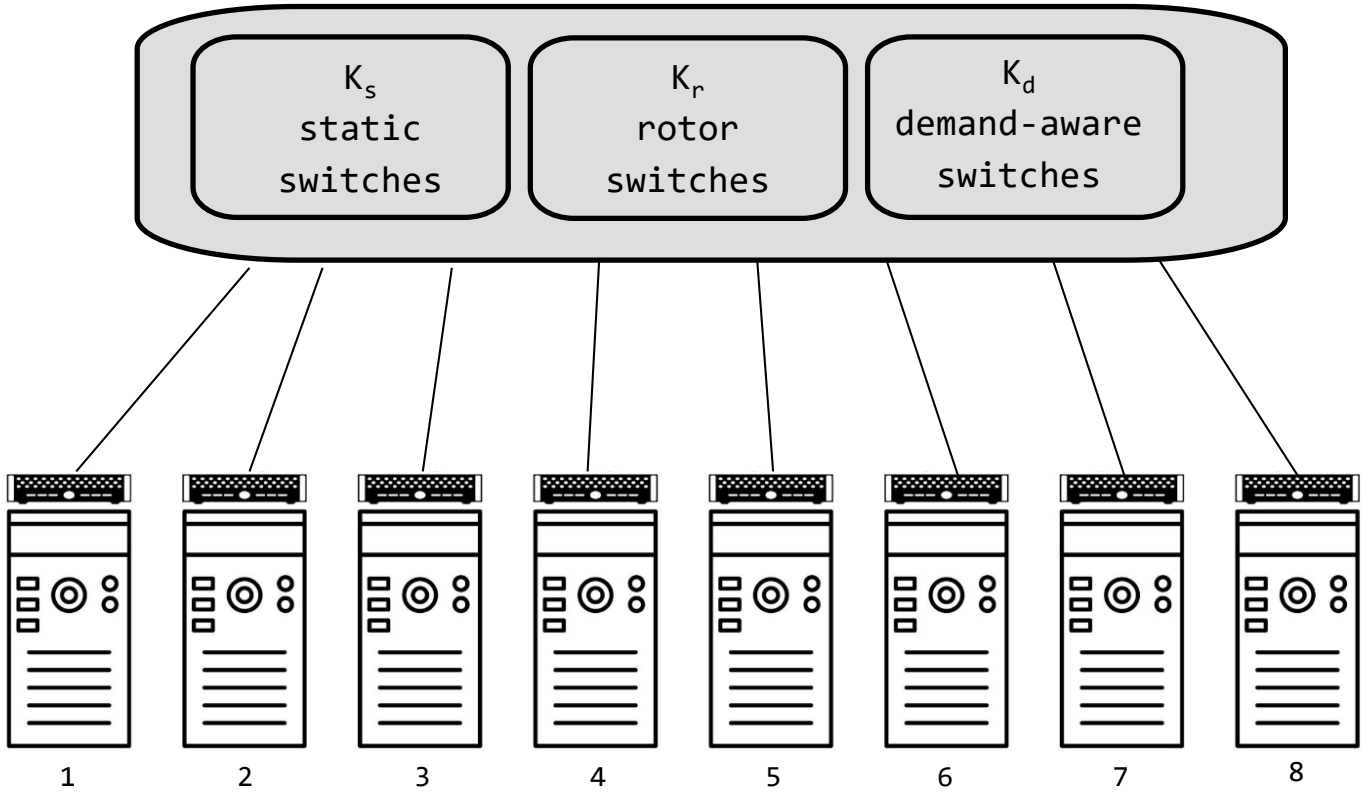
⇢ **Observation 3:** For small flows, flow completion time suffers if network needs to be reconfigured first.

⇢ **Observation 4:** For large flows, reconfiguration time may amortize.

Cerberus



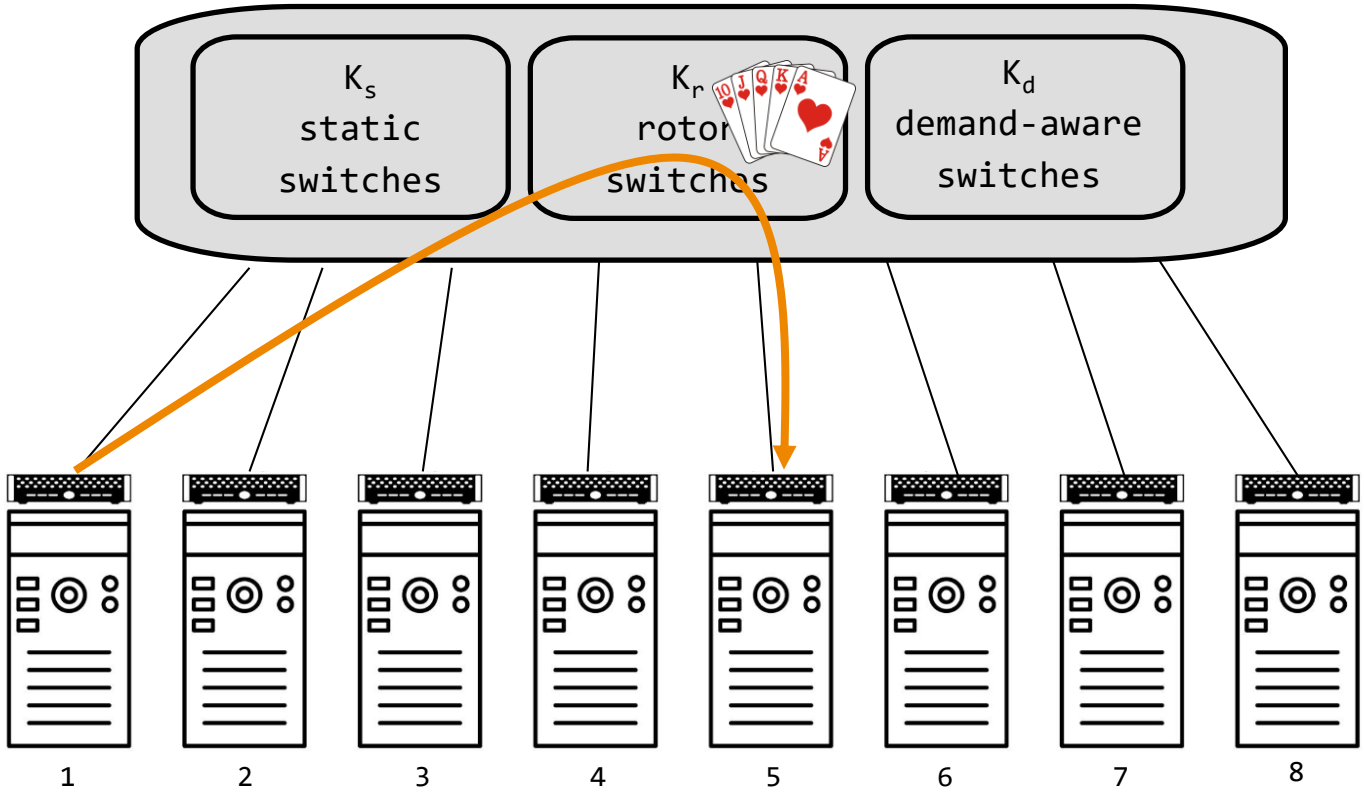
Cerberus


K_s
static
switches
K_r
rotor
switches
K_d
demand-aware
switches
1
2
3
4
5
6
7
8

Cerberus

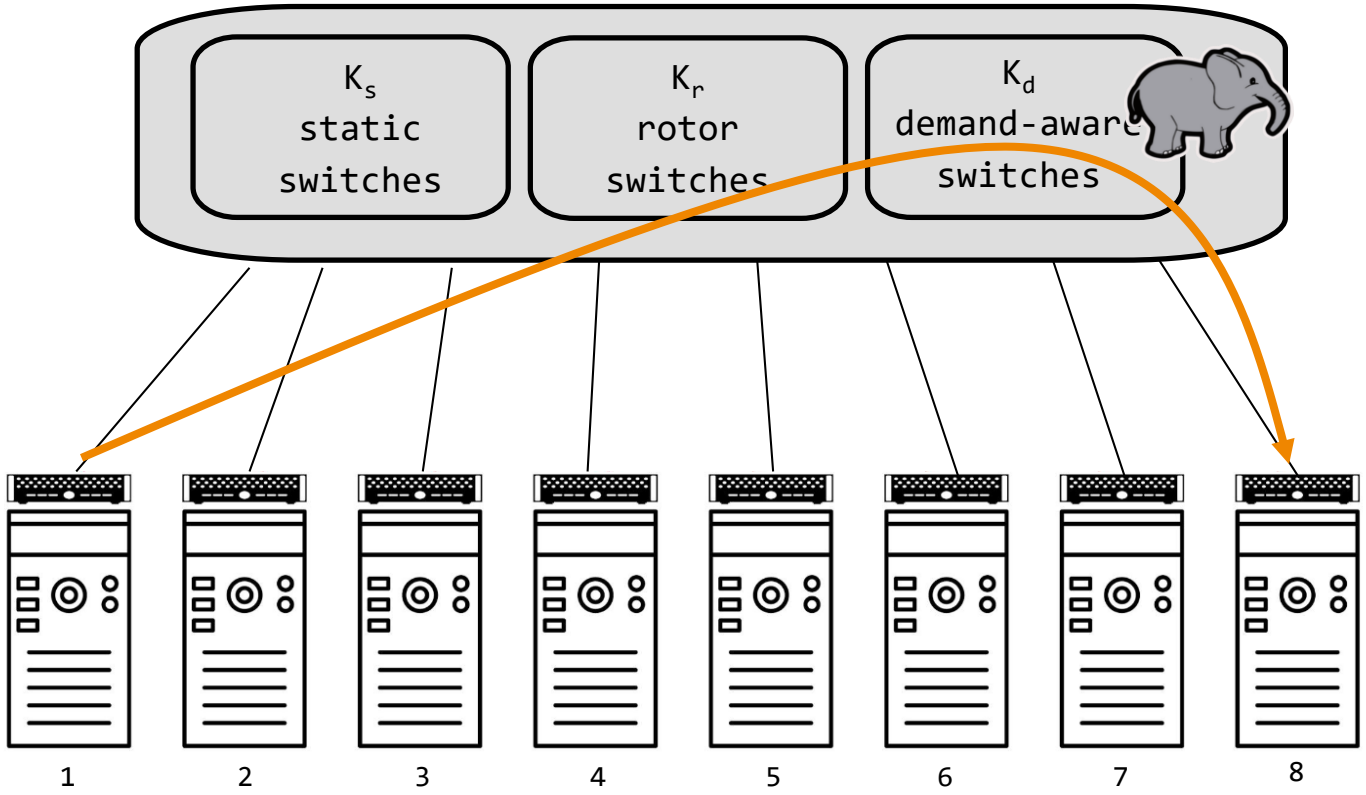
Scheduling: Small flows go via static switches…

Cerberus



Scheduling: … medium flows via rotor switches…

Cerberus

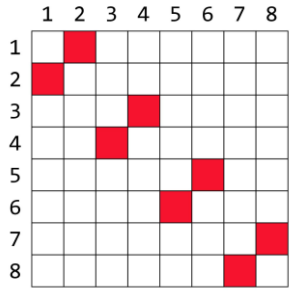


Scheduling: … and large flows via demand-aware switches (if one available, otherwise via rotor).

Throughput Analysis

Demand Matrix

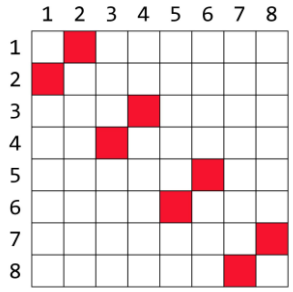
T



Metric: throughput of a demand matrix…

Throughput Analysis

Demand Matrix

T 

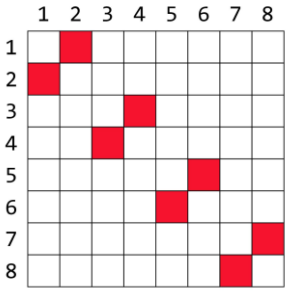
$\times\ \theta(T)$

Metric: throughput of a demand matrix…

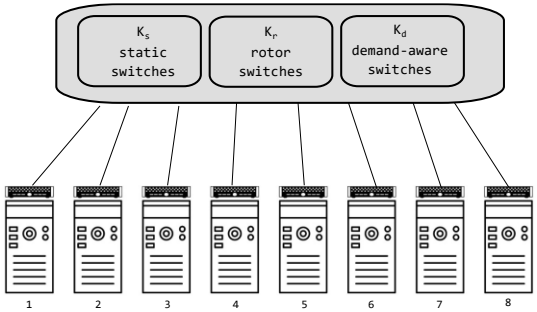
… is the maximal scale down factor by which traffic is feasible.

Throughput Analysis

Demand Matrix

T 

$\times\ \theta(T) \quad \Rightarrow$



Metric: throughput of a demand matrix…

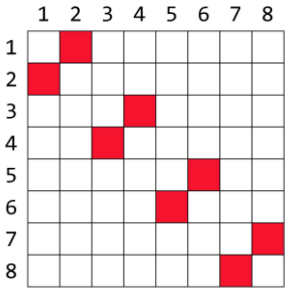
… is the maximal scale down factor by which traffic is feasible.

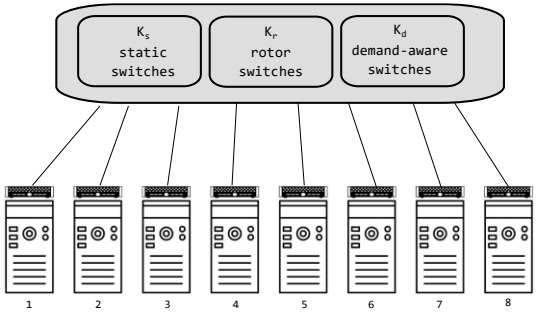
Throughput of network θ^*: worst case T

Throughput Analysis

Demand Matrix

$$T \times \theta(T) \Rightarrow$$



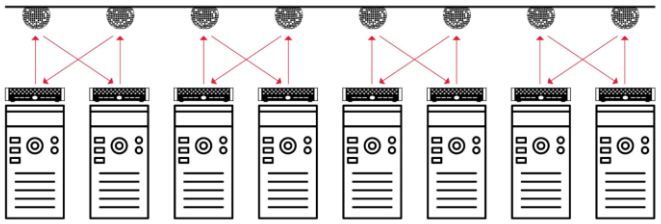


BW tax!

BW & latency tax!

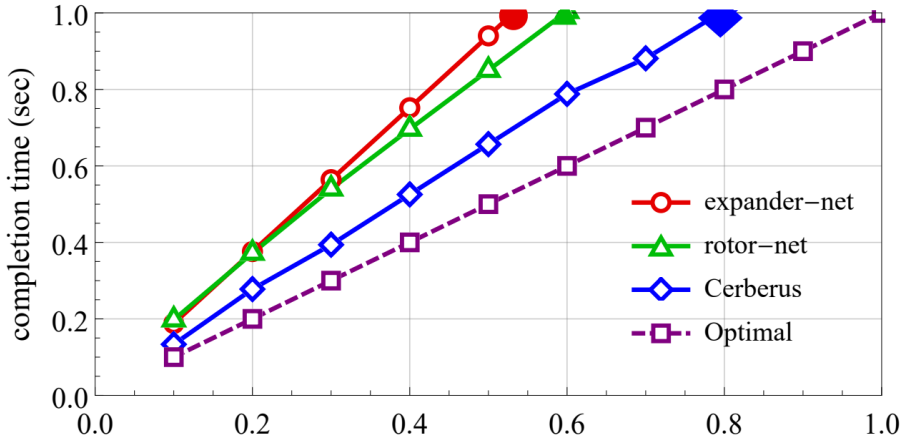
	expander-net	*rotor-net*	CERBERUS
BW-Tax	✓	✓	✗
LT-Tax	✗	✓	✓
$\theta(T)$	Thm 2	Thm 3	Thm 5
θ^*	0.53	0.45	Open
Datamining	0.53	0.6	0.8 (+33%)
Permutation	0.53	0.45	≈ 1 (+88%)
Case Study	0.53	0.66	0.9 (+36%)

Worst demand matrix for static and rotor: permutation. Best case for demand-aware!



Completion Time

⇢ Demand completion time: How long does it take to serve a demand matrix?



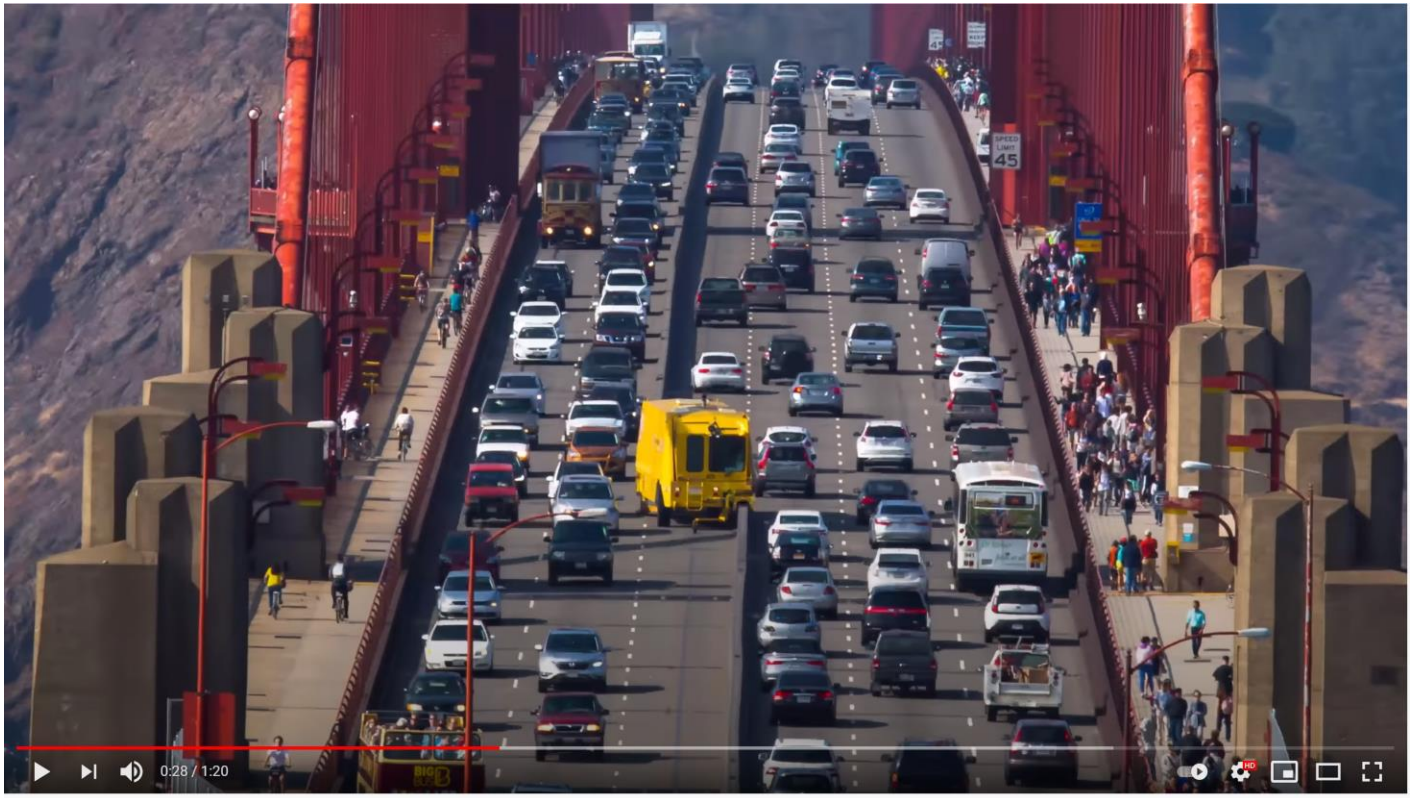
Data mining workload

⇢ Also useful in analysis: throughput can be computed more easily via demand completion time.

Bonus Material

Hogwarts Stair

Bonus Material



Golden Gate Zipper

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By **Michelle Hampson**

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In HPC